Ice Conditions in Great Mosquito Cove, Trinity Bay Newfoundland

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Project Team

Greg Crocker, Ph.D.,
Research Scientist

Abigail Steel, M.Eng.,
Research Engineer

Denny Christian,
Group Leader, Technical Support

Abstract

Ice conditions in Great Mosquito Cove, Trinity Bay, Newfoundland, were observed during the period from January 15 through May 14, 1990. Twice-weekly observations were made of ice distributions and ice types in the cove and the adjacent reaches of Bull Arm. Ice thickness and snow depth were measured on an opportunistic basis, when ever conditions permitted safe access to the ice surface. The salinity profile and crystal structure of the ice was determined from an ice block extracted on March 22. An automatic weather station was set up in the west end of the cove and recorded air temperature once every 15 minutes throughout the entire observation period. This data was used to assess the some of the climatological differences between Great Mosquito Cove and nearby Sunnyside, where a nearly continuous temperature record exists for the past 17 years. This historical data was then used as input to a thermodynamic ice growth model. The model was used to predict minimum, maximum, and mean ice conditions in the cove, based on the historical temperature record. A survey of several residents of Sunnyside provided additional information about the historical ice conditions in this area. All of this information has been used to predict what ice conditions might be experienced in Great Mosquito Cove in the near future, with particular reference to the proposed development.

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1 Introduction

The objective of this project was to determine ice conditions in Great Mosquito Cove, Trinity Bay, Newfoundland. This area is currently being considered as the construction site for the gravity based structure to be used at the Hibernia oil field. Geographically and topographically the site is well suited to this task, but very little was known about ice conditions in this part of Trinity Bay, and the impact ice might have on the development and construction phases of the project. As a result, the study was designed to determine ice conditions in Great Mosquito Cove with an emphasis on aspects of the ice climatology which may impede (or enhance) the proposed development.

Two main tasks were identified. The first was to monitor the spatial and temporal variations of ice in Mosquito Cove during the 1990 ice season, and to quantify the relevant physical properties of the ice cover. The second was to provide an estimate of the likely range of ice conditions at the site over the proposed life of the development. The techniques used in achieving these goals are described in the relevant sections below.

The project officially began on December 18, 1989, at which time the necessary instrumentation was ordered and the observation procedures established. On January 5, 1990 a preliminary trip to Sunnyside (see figure 1) was undertaken and arrangements made for two local residents to conduct the routine (twice-weekly) field observations. The first trip to Great Mosquito Cove was on January 10. At this time an overland route was established (utilizing pre-existing trails as much as possible) and a suitable site for the automatic weather station (AWS) identified. On January 15 the AWS was set up and the observations period began. Observations continued until May 14, 1990, when the weather station was dismantled and the field portion of the programme ended. Data analysis, interviews with local residents, and ice growth modelling were conducted during the following months, and the project ended on August 31, when the final report was submitted.

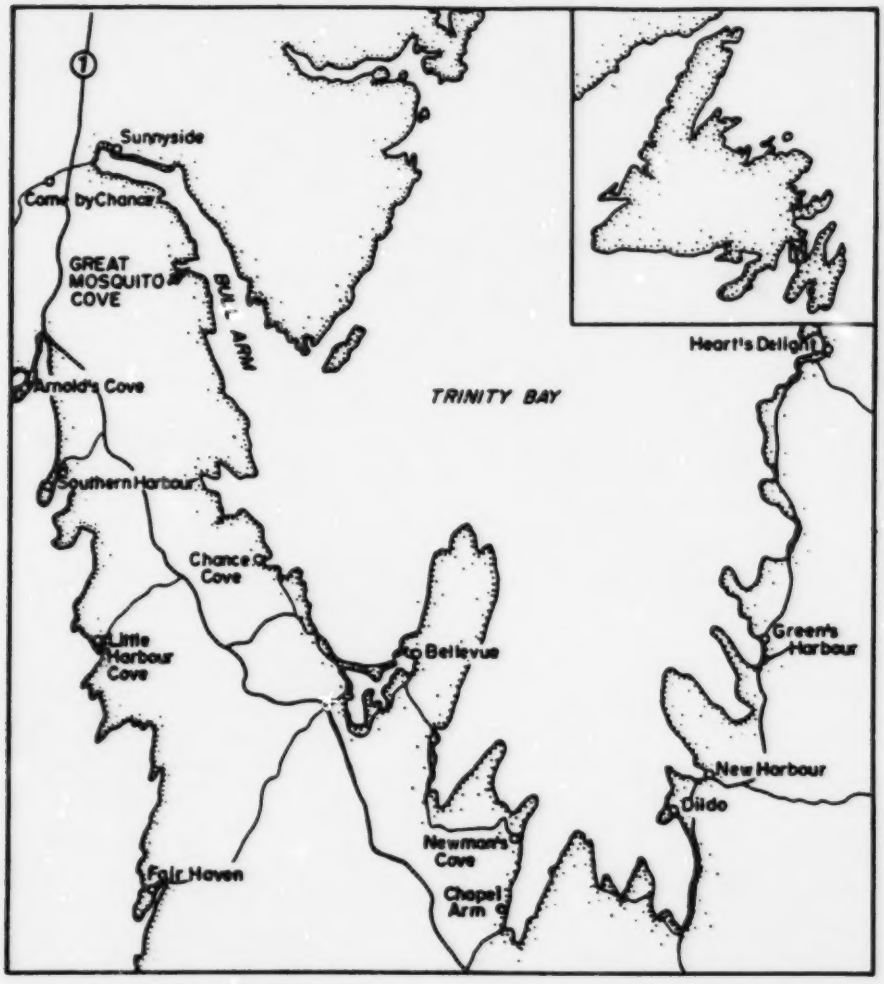


Figure 1. Location map showing the Trinity Bay, Bull Arm, Great Mosquito Cove region.

2 Ice Conditions: Winter 1990

2.1 Measurement Techniques

Ice observations were made twice-weekly throughout the January 15 to May 14 field programme. These routine surveys were conducted by two residents of nearby Sunnyside who travelled to the site overland on all terrain vehicles. On each trip a map was drawn showing the locations and types of ice in Great Mosquito Cove and the section of Bull Arm at its entrance. Photographs of the cove were taken from a knoll near the AWS site, and whenever possible, ice thickness measurements were made with an auger and metre stick.

In addition to these regular observations, additional information on ice conditions and properties was obtained by two persons from C-CORE, who travelled to the site approximately once every three weeks to check the AWS and dump the data to cassette tapes for transfer to an EMPaC personal computer. General ice conditions were mapped during these visits as well, and whenever possible (that is, whenever ice conditions were regarded as being safe for access and movement on the surface), ice thicknesses were measured. Ice thicknesses were obtained by drilling a hole through the ice with a hand auger, and measuring the distance from the lower to the upper surfaces by means of a metre stick with a small 'L' bracket on the end which was used to hook the underside of the ice. On March 22 an ice block was cut from the inner portion of the cove and transported to St. John's for analyses of the salinity profile and crystal structure.

The automatic weather station was comprised entirely of instrumentation leased from the Campbell Scientific Canada Corporation. This equipment has been used by C-CORE personnel on numerous previous studies and has proven both rugged and reliable. The configuration used here included a temperature probe, radiation shield, 21X data logger, data logger housing, and a tripod on which the instruments were mounted. The temperature probe was mounted 2.0 m above the ground. The AWS was powered by a 12 volt automobile battery kept in a protective box at the base of the tripod. Because of the low power requirements of the instruments, this single battery supplied ample power for the duration of the field programme without requiring recharging. The data logger was programmed such that a single

temperature measurement was performed and stored once every 15 minutes. As the data logger's memory capacity was slightly over 19,000 data values, it could run for over three weeks before filling up and requiring a data dump. The AWS was located in the north west corner of the cove, in a small clearing near the inflow point of a small stream (figure 2). It was approximately 10 m from the water and approximately 3 m above mean sea level. The automatic weather station was set up on January 15 and taken down on May 14, and collected data continuously during the entire measurement period.

2.2 Ice Regime

Ice conditions in Great Mosquito Cove during the 1990 ice season are shown in figures A1 through A40 (appendix A). Between the 10th of January, when the first observations were made, and the 6th of February, ice in the cove was limited to small patches near the freshwater inflows. This ice tended to form overnight, reach thicknesses of only 3 to 5 cm, then melt during the afternoon. It usually consisted of small cakes, less than 1m in diameter, and made up of unconsolidated frazil or slush (see Appendix B for definitions of ice types used in this report).

On February 6, a uniform, consolidated ice cover formed on the inner third of Mosquito Cove (figure A10). This ice was approximately 5 cm thick, and had a smooth surface spotted with frost flowers. The presence of frost flowers indicates that the forming ice was saline (frost flower growth is associated with the upward migration of brine through the ice in the early stages of formation). Salinity profiles taken later in the season confirmed this observation. Although the ice was a solid mass at this time, it was far to weak to support a person.

This ice sheet continued to thicken until some time between the 16th and 19th of February when a complete break-out occurred. The ice reached a thickness of about 30 cm before breaking up. Its lateral extent did not change appreciably during this period, although it appears that outer 200 m broke off several days before the complete break-out.

On February 23, a new ice sheet of roughly the same extent, and about 20 cm thick, had already formed. This ice continued to thicken until reaching its maximum observed thickness of 41 cm on March 10. By February 27,

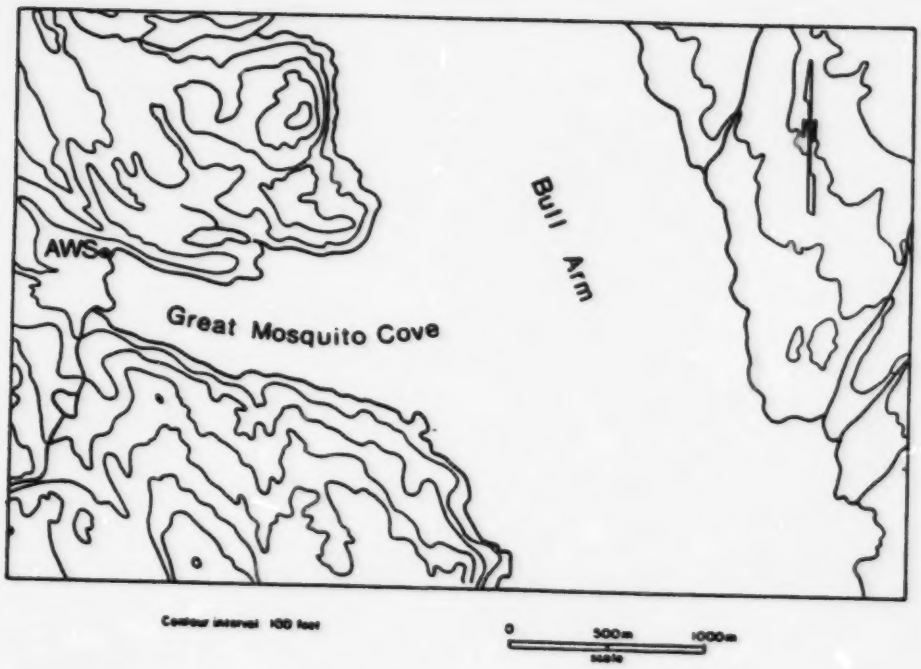


Figure 2. Topographic map of Great Mosquito Cove, showing the location of the automatic weather station.

a landfast ice sheet had formed over all of Great Mosquito Cove and the visible portions of Bull Arm. This entire area remained frozen until the 16th of March, when it broke out to a line across Bull Arm immediately south of the mouth of Mosquito Cove (figure A24). By March 24, all of the ice in this section of Bull Arm had broken out, leaving only the inner half of Mosquito Cove ice covered. At the same time as this progressive breakup was occurring, the ice was thinning. This was due primarily to ablation at the underside of the ice, suggesting an increase in water temperature and/or reduced heat flow through the ice mass (these processes are discussed in detail in section 3). No ice thickness measurements were made after March 21, as the ice was deemed unsafe for access. The inner half of the cove remained frozen until April 10, when the ice broke out completely. No ice of any type was observed in Great Mosquito Cove after this date.

On March 13 a transect of 10 ice thickness measurements was made from the inner most section of the cove, roughly 800 m out toward the cove entrance (figure 3, figure A23). The data shows that the ice thickness was fairly uniform over the entire cove, indicating that the spot measurements used to produce the thickness time series should be representative of the overall conditions of the ice cover. It is not clear what caused the slight increase in ice thickness about 300 m from shore. It may be a result of some rafting of ice or build up of slush at the ice edge during the initial stages of ice sheet formation.

2.3 Ice Properties

In addition to ice extent and thickness, several other basic physical properties are normally used to characterize an ice cover. Knowledge of the crystal structure, salinity, temperature, and brine volume, allows estimates to be made of the mechanical properties of the ice, which are important to engineering activities in ice infested water (Ashton, 1986; Gold, 1977)

Although a time series of these physical properties could not be obtained in Mosquito Cove due to the unsafe nature of the ice throughout most of the season, a single ice block was extracted on March 22, which provided a considerable amount of information on the characteristics of the ice sheet. On this date an ice sample was cut from surface of the cove with an ice saw,

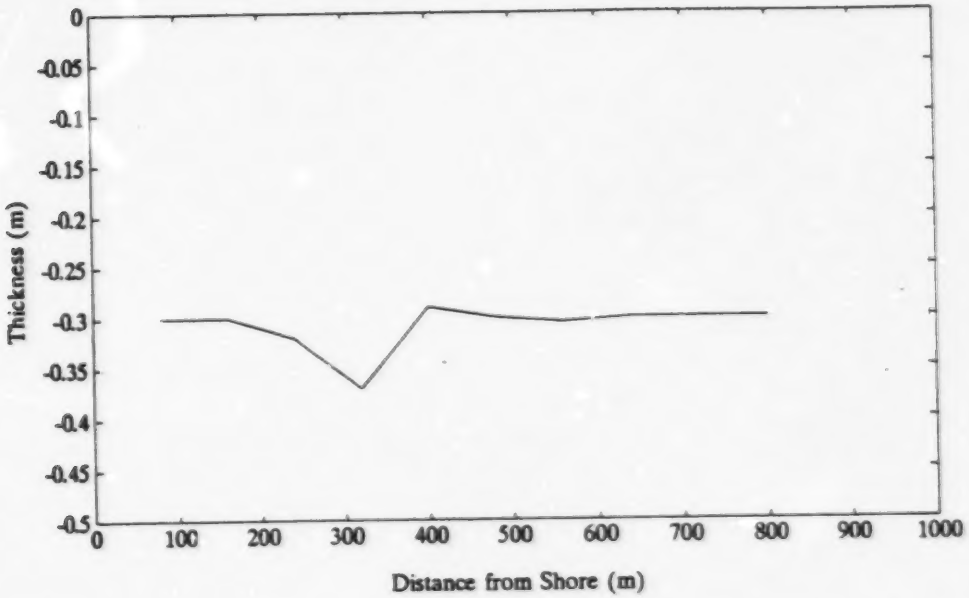


Figure 3. Ice thickness transect, March 13, 1990.

wrapped in insulation and transported to St. John's in a cooler filled with dry ice. The block, which was about 27 cm thick, was subdivided into two samples, and analysed for crystal structure and salinity.

Because it is virtually impossible to determine the crystal structure of ice with the naked eye in white light, a technique has been developed in which polarized light is used make the individual crystals in the ice matrix clearly visible. The details of the optical physics behind this technique, and of the exact procedure followed, can be found in Hobbs (1974) and Langway (1958) among others. In general, a section of the core (either a vertical or horizontal slice) is frozen to a glass plate and planed to a thickness of about 1 mm on a microtome. This thin section is then placed between crossed polaroid filters and photographed. Since ice crystals are optically bifringent, light passing through the two polarizing filters and the thin section exits with a range of intensities and colours, depending on the orientation of the crystal. In effect, each crystal appears a different colour and with a different brightness. From these crossed polaroid photographs, the detailed structure can be examined. The crystal structure of the March 22 core is illustrated schematically in figure 4. The ice was composed of three well defined layers. From the surface down to a depth of 6 cm there was a polycrystalline layer, with well rounded crystals approximately 0.2 cm in diameter. This structure is characteristic of fresh water ice, and must have been formed by the freezing of rain water and/or melted snow on the surface of the existing ice cover. Bonding between this layer and the bulk of the ice sheet below was very weak (in fact this surface layer easily separated from the lower portion of the core during extraction). Below this was a well defined layer of ice composed of small, randomly oriented crystals, formed from frazil and or slush on the water surface during the initial stages of ice growth. The crystals in this layer were slightly elongated, with a long axis length of about 0.2 cm and a short axis of about 0.1 cm in length. Beneath the frazil layer, which was 4 cm thick, the remainder of the ice sheet showed the distinctive columnar structure characteristic of slow steady growth. In this layer, variations in the thermal properties of the crystals lead to gradual orientation of their long axes in the vertical; the crystals with their 'a' crystallographic axes parallel to the direction of heat transfer growing more rapidly than those with other orientations. The size of the crystals also changes with depth, from typical sizes of 0.2 $\times$ 0.15 cm near the top, to 0.5 $\times$ 2.5 cm at the base.

The marks on the left side of the core indicate the average depths of the sections analysed for salinity. The salinity profile from the core is shown in figure 5. Sea ice formed from typical sea water, with a salinity of 32 to 34 parts per thousand (ppt), normally retains about 15% of the salts in the water, giving ice salinities of 4 to 6 ppt. Clearly the ice in Great Mosquito Cove is much less saline than this, particularly near the upper and lower surfaces. This is of considerable importance, as the salinity of the ice greatly influences its strength properties. It results from two related processes. The first is fresh water runoff. Because Bull Arm, and Mosquito Cove in particular, are quite sheltered, the fresh water which flows in from rivers and streams is not well mixed with the saline sea water. Although wind and wave induced mixing do occur during periods of open water, the sea water is diluted and can have salt contents well below that of water in the open ocean. It follows that ice formed from low salinity water will also have a lower salt content. This is the reason for the relatively low (0.6 to 0.7 ppt) salinities in the middle sections of the ice sheet, which were formed from vertically mixed water column during the early stages of growth. Once an ice cover has formed, wind and wave induced mixing are severely limited (the wind can not act directly on the water surface) and subsequent fresh water inflow tends to float out under the ice and form a fresh layer on top of the more saline water already in the bay. This phenomenon is common in sheltered bays and inlets and results from the fresh water being less dense than the salt water. All subsequent ice growth at the ice/water interface occurs in this relatively fresh layer, resulting in very low ice salinities as seen at the bottom of the Great Mosquito Cove core. A spot sample of the water filling one of the holes drilled on March 13 showed a salinity of 5 ppt, but it is uncertain how much mixing in the upper water column resulted from the drilling process. The low salinity (0.1 ppt) seen in the top layer is clearly due to the fact that this ice was formed primarily from snow and/or rain, which is of course fresh.

Two additional ice properties which have a bearing on the mechanical behaviour of ice are the temperature and the brine volume. Although ice temperatures were not measured, the temperature profile can be estimated from the air temperature and the freezing temperature of the water. Using air temperature (T_a) as an estimate of the ice surface temperature (T_s) is only possible when there is little or no snowcover (since snow is a good insulator it

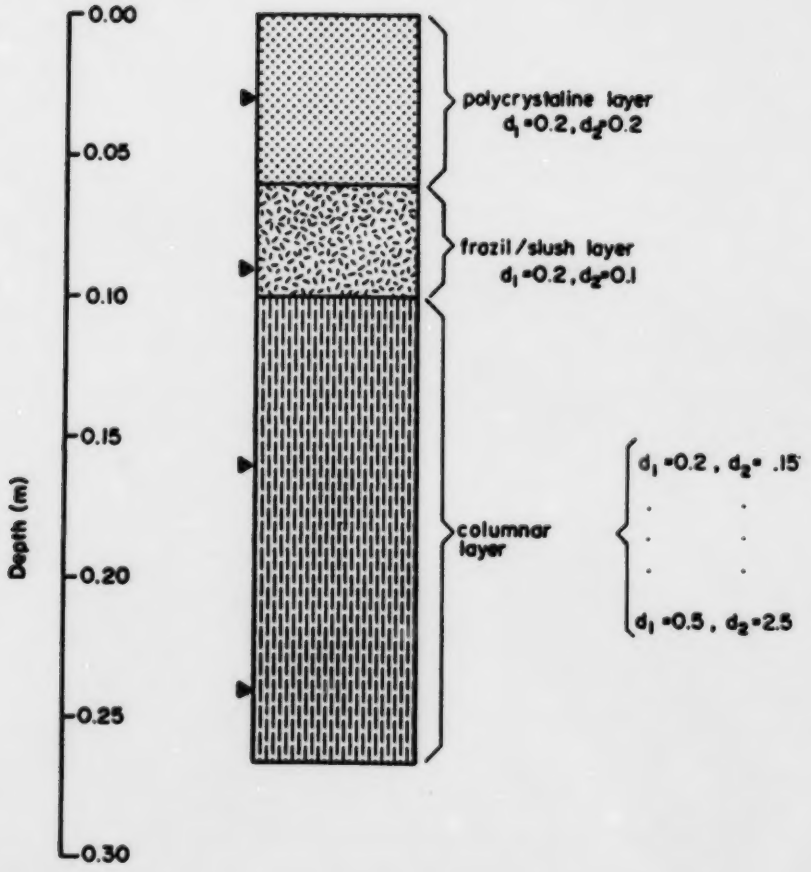


Figure 4. Schematic representation of the crystal structure observed in the core taken March 22, 1990.

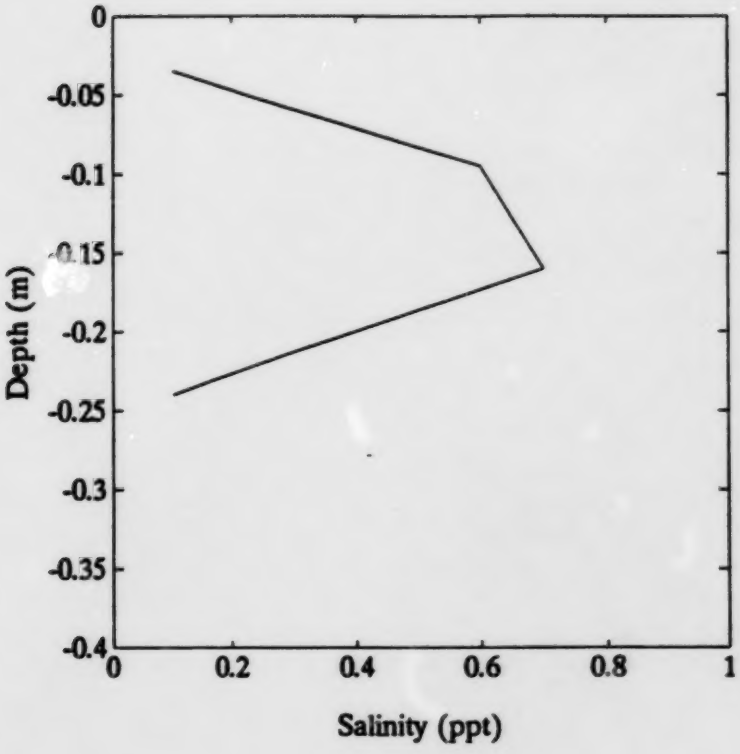


Figure 5. Salinity profile from the March 22, 1990 ice core.

tends to cause an increase in ice temperatures). However, with the exception of a brief period around March 13, when two to three centimetres of snow was observed, the ice in Mosquito Cove remained virtually snow free. The temperature at the base of the ice sheet (T_b) must be at or near to the salinity determined freezing point; in this case with a salinity of 5 ppt, $T_b \approx -0.3\,°C$. The profile can then be assumed to be linear between these two boundaries, a characteristic well documented in numerous investigations of growing sea ice (Nakawo and Sinha, 1981, for example).

These assumptions allow us estimate the ice temperature (T_i) at any depth as a function of T_s. Although the variability in air temperatures prevents any single 'representative' profile from being defined, a reasonable range of profiles can be defined, based on the observed range in T_s. With air temperatures of -10, -5, and -2 °C, the mean ice temperatures will be -5.1, -2.6, and -1.1 °C respectively.

More importantly from an engineering standpoint, the temperature profiles can be coupled with the measured salinities to produce a range of likely brine volume profiles. Here the term brine volume refers to the proportion of liquid brine in the ice per unit volume, usually expressed in units of parts per thousand. The brine volume profiles shown in figure 6 have been calculated using the equations of Frankenstein and Garner (1967). They indicate that brine volumes in the ice in Mosquito Cove are quite low, except at temperatures very near the freezing point. This suggests that the mechanical behaviour of the ice sheet will be similar to that of freshwater ice, except at high temperatures when brine volume may become important, and should be considered when estimating mechanical properties.

Empirical relations based on brine volume can be used to estimate many important engineering properties of ice, such as Young's modulus, Poisson's ratio, compressive strength, tensile strength, shear strength, and flexural strength. Many of these relationships involve other parameters (such as strain rate) and will not be estimated here. They can however, be determined from the brine volume profiles presented above, as required.

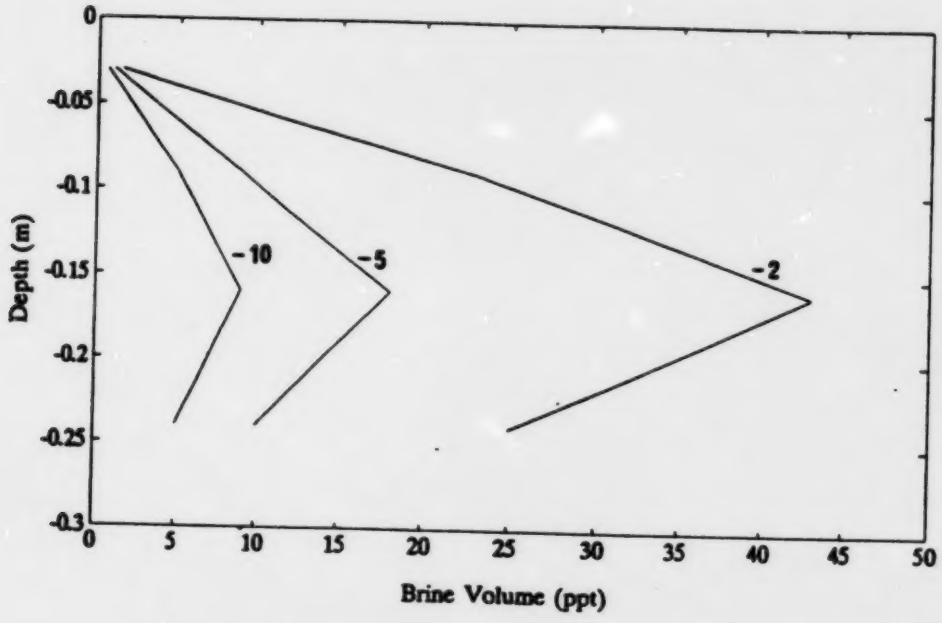


Figure 6. Estimated brine volume profiles for surface temperatures of −10, −5, and −2 °C, and the measured salinities.

3 Seasonal Variability

3.1 Introduction

In section 2, detailed observations of the occurrence, extent and properties of the ice in Great Mosquito Cove during the 1990 ice season have been presented. However, these observations can not *a priori* be assumed to be representative of typical ice conditions in this area. To determine what the range of ice conditions might be, what conditions are likely in a 'normal' winter, and how representative the 1990 observations are, two different approaches will be taken. The first will be the development of an ice growth model which can be used to hindcast ice conditions over a period of 10 to 20 years. The second will utilize local knowledge of ice conditions over this same interval.

3.2 Modelling

In order to predict what ice conditions might have been like in Great Mosquito Cove during the past 10 to 20 years, we must have a representative record of air temperatures at the site. The Atmospheric Environment Service (AES) has operated a limited weather station in the nearby community of Sunnyside since 1972 (recording daily maximum, minimum, and mean temperature), but temperatures recorded here are not necessarily representative of conditions in Mosquito Cove. Therefore, before beginning any modelling studies the relationship between the temperatures at the two locations must first be established. To this end, the automatic weather station described earlier was set up in Great Mosquito Cove and operated throughout the ice observation period.

The recorded mean daily temperatures are shown in figure 7. This most striking feature of this data set is the extreme variability in air temperature. The mean temperature during the 119 day period was -3.3 °C, but temperatures ranged from a high of $+16.4$ to a low of -27.2 °C. Also notable is the apparent change in temperature patterns on about day 90. At this time the extreme low temperatures and high variability seemed to end, and a more temperate pattern emerged. In this and all subsequent figures the time scale is given in Julian Days, that is, the number of days from the beginning of

the year (January 1 is day 1, December 31 is day 365).

Figure 8 shows the same data along with the concurrent mean daily temperatures recorded at Sunnyside. Clearly the patterns are quite similar, although, there are frequently several degrees difference in the extremely high and extremely low temperatures. Figures 9 and 10 show the daily maxima and minima at the two sites. Again the patterns are quite similar, but the magnitudes vary somewhat. In particular, the very cold days occasionally exhibit quite large differences.

These relationships can be seen more easily in figures 11, 12, and 13. These plots show that the mean and maximum temperatures are strongly correlated (although the scatter in the daily maxima is slightly larger). However, the daily minima at Great Mosquito Cove are consistently lower than those at Sunnyside. There is also much greater variability between the sites. This variability is not surprising given the atmospheric conditions that are normally responsible for bringing about very low temperatures. Extreme minima most often result from low level inversions on cold clear and calm nights. Under these conditions longwave radiative losses from the surface can be substantial, and if there is no wind to break down the low level stratification, temperatures at the surface can fall to 5 or 10 °C below those several metres above the ground. The consistent occurrence of lower temperatures in Great Mosquito Cove therefore suggests the site is more sheltered from winds, at least in the interior part of the cove where the temperatures were measured. A quick look at the local topography bears this out.

It is also interesting to compare this years Sunnyside data with the historical record. Figure 14 shows the mean daily temperatures measured in the winter of 1990, along with the average mean daily temperatures recorded over the same period during the past 17 years. As the historical record is averaged there is much less variability, but it is evident that temperatures during the early part of the season were significantly colder in 1990 than on average. The mean temperature between days 15 and 70 was −7.5 °C, while on average the temperature during this interval is −5.4 °C.

In most simple ice growth models, including those which will be tested here, an additional temperature index, the 'freezing degree day', is particularly important. Freezing degree days are simply the cumulative daily

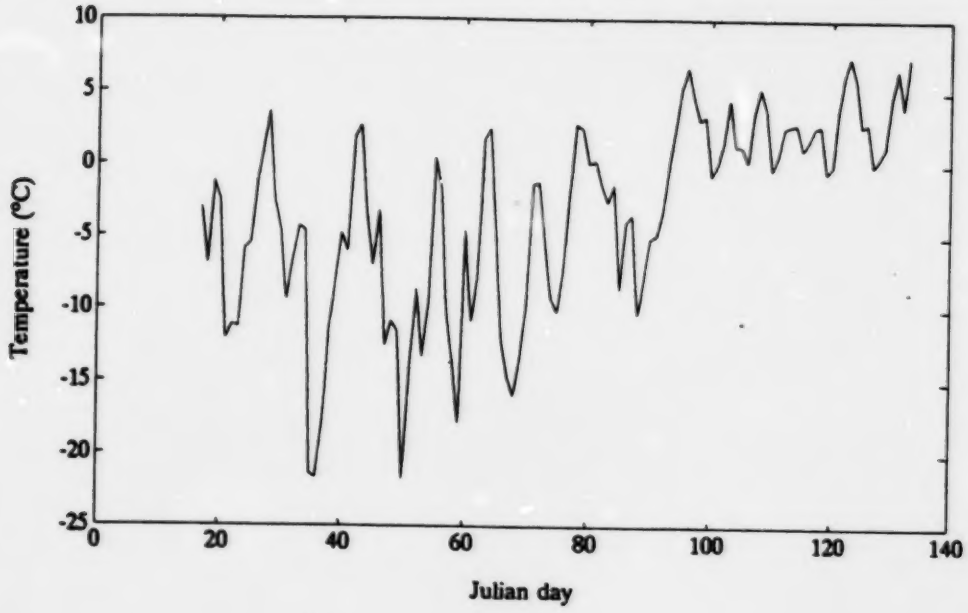


Figure 7. Measured mean daily temperatures in Great Mosquito Cove, January 15 through May 14, 1990.

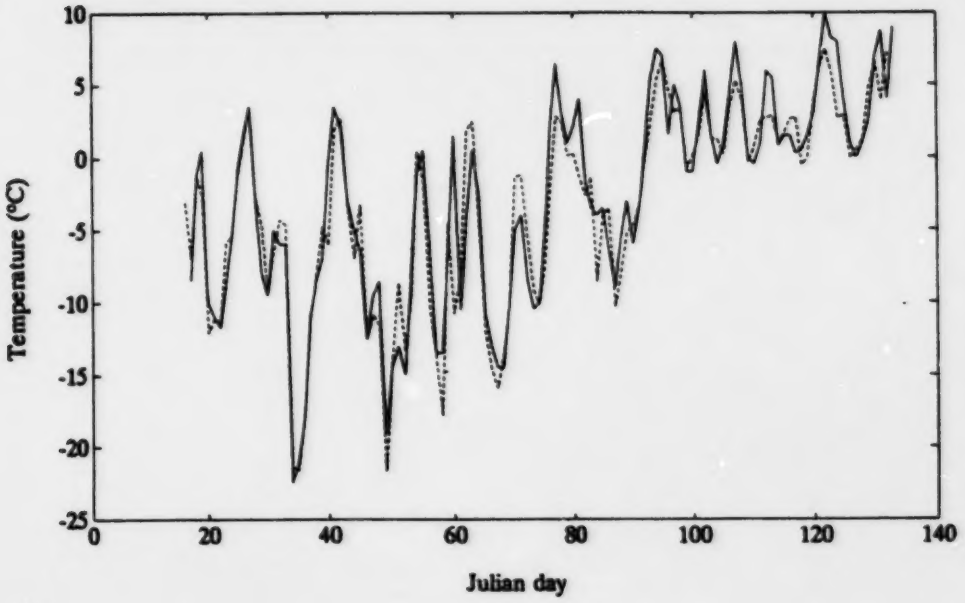


Figure 8. Mean daily temperatures from Great Mosquito Cove (dashed line) and Sunnyside (solid line), January 15 through May 14, 1990.

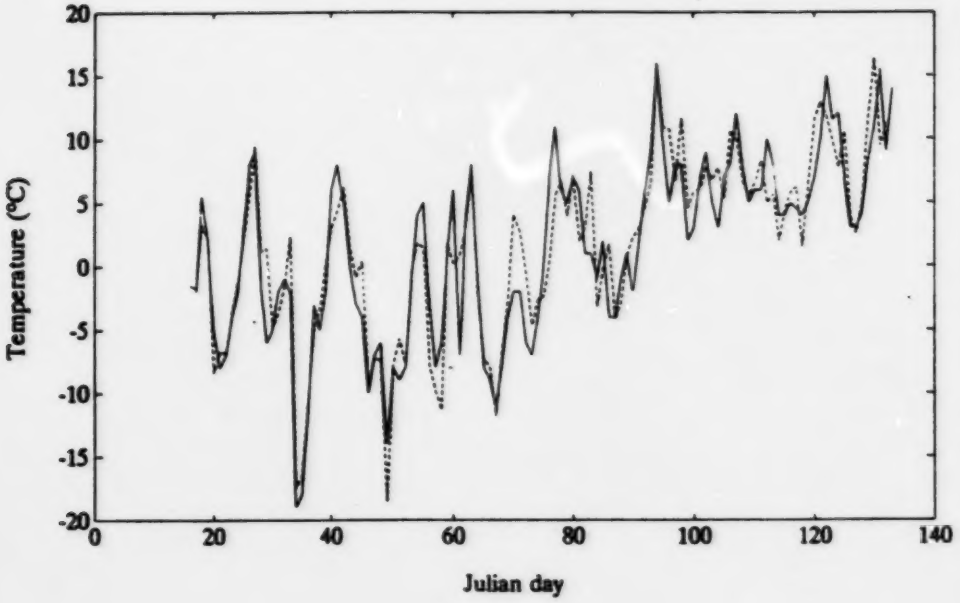


Figure 9. Daily maximum temperature in Great Mosquito Cove (dashed line) and Sunnyside (solid line), January 15 through may 14, 1990.

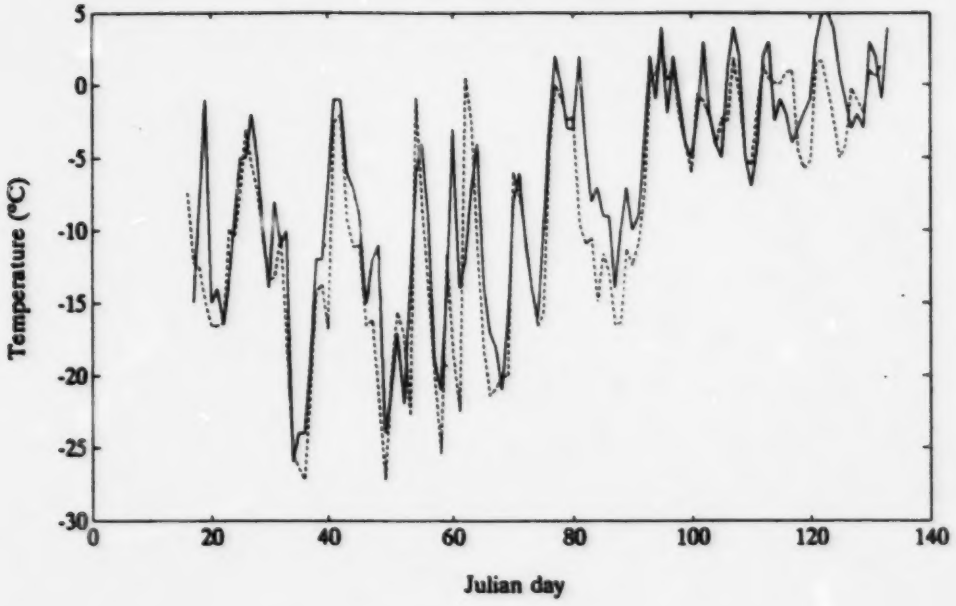


Figure 10. Daily minimum temperatures in Great Mosquito Cove (dashed line) and Sunnyside (solid line), January 15 through May 14, 1990.

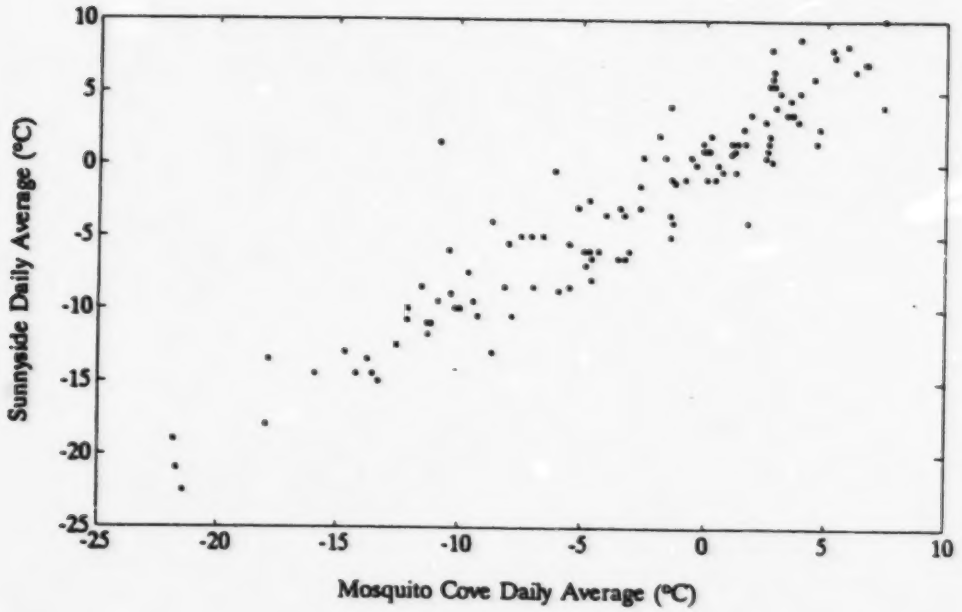


Figure 11. Great Mosquito Cove mean daily temperature versus Sunnyside mean daily temperature.

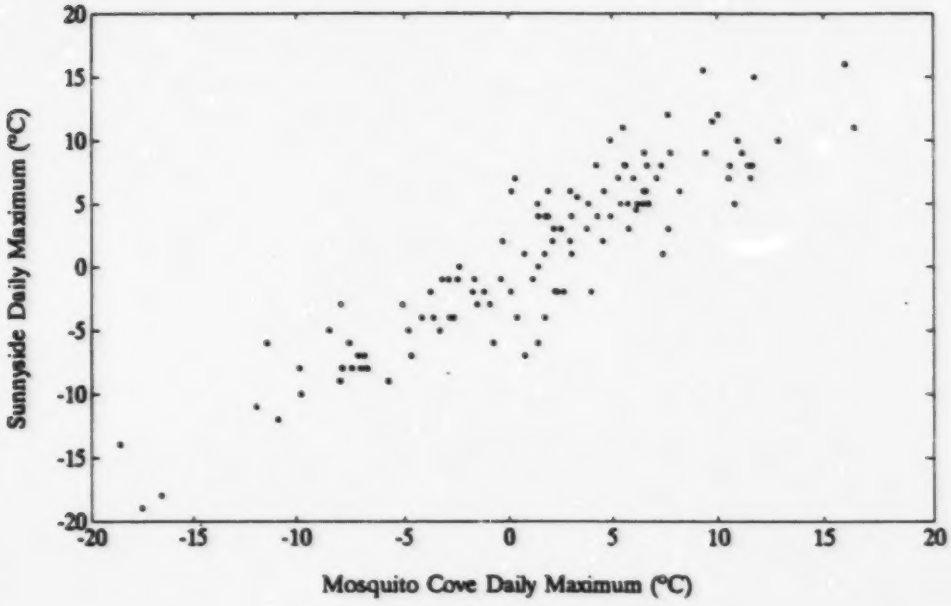


Figure 12. Great Mosquito Cove daily maximum temperature versus Sunnyside daily maximum temperature.

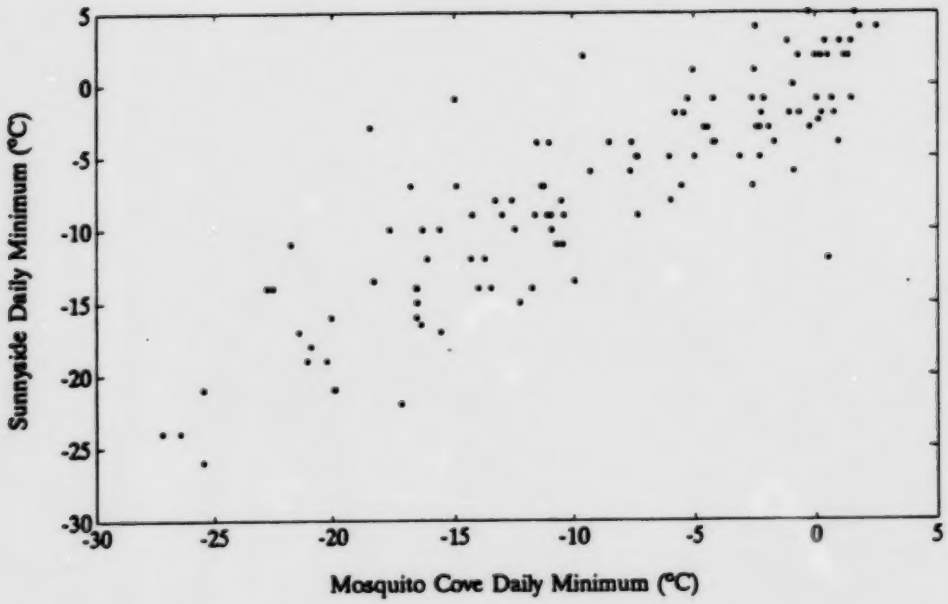


Figure 13. Great Mosquito Cove daily minimum temperature versus Sunnyside daily minimum temperature.

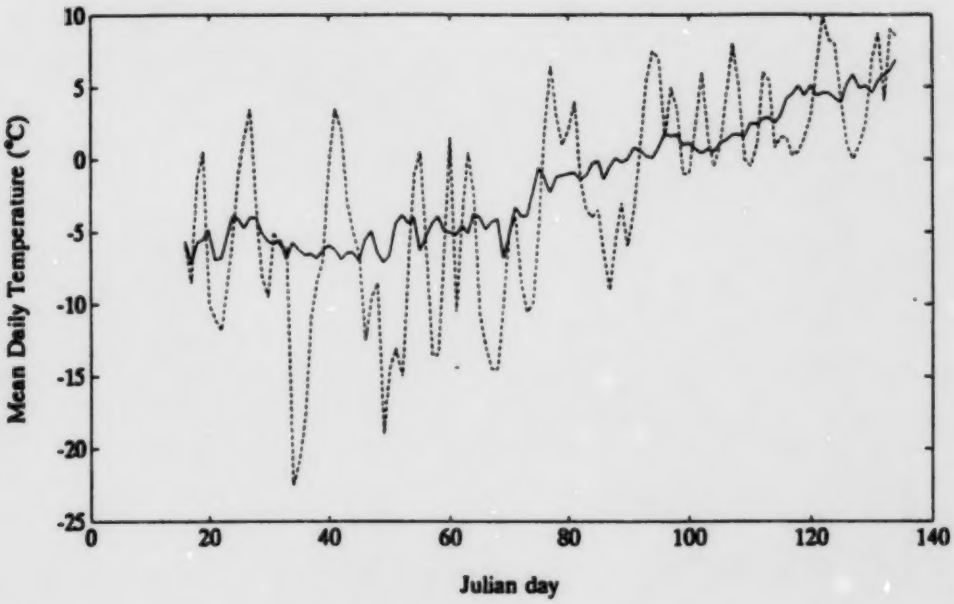


Figure 14. Mean daily temperatures at Sunnyside in 1990, and the historical average (17 years).

temperature below the freezing point. For example, if the freezing temperature is assumed to be 0 °C, and temperatures on the first three days of growth are −5, −12, and −10 °C, then the freezing degree day index after 3 days will be −27 °C. It easy to see that because ice growth is cumulative, small differences in air temperatures can add up to produce large differences in the total heat loss, and therefore ice growth. Freezing degree days for the 1990 Great Mosquito Cove data, the 1990 Sunnyside data, and the historical Sunnyside data are shown in figure 15. Here it can be seen that the 1990 season was considerable colder (from an ice growth perspective) than the average winter. It can also be seen that the relatively small differences in air temperatures between Mosquito Cove and Sunnyside during 1990 add up to produce a roughly 15% difference in freezing power by the end of the ice growth period. Although this difference coresponds roughly to a 7% difference in predicted ice thickness, it is probably within the errors associated with the ice growth hindcasting. We will therefore use the unmodified historical Sunnyside data in the hindcasting study, but must keep in mind the possible effects on the ice thickness predictions.

Thermodynamic ice growth models generally fit into one of two categories; those based simply on freezing degree days, and those which incorporate the effects of all the atmospheric and oceanic processes which contribute to ice growth and decay Semtner, 1976, for example). In this study we will look only at the simpler freezing degree day models, as they have been shown on numerous occasions to accurately forecast ice growth in specific locations, once the necessary empirical or semi-empirical parameters have been properly set. Also, air temperature is the only available input parameter for the site in question.

The earliest, and still one of the most widely used, degree day model was developed by Stefan (1889). He showed that subject to a certain set of assumptions, ice thickness at any time (t) can be determined by

$$h^2 = \frac{2k_i}{\rho_i L_f} \int (T_m - T_a)\, dt, \tag{1}$$

where k_i is the thermal conductivity of the ice, ρ_i is the ice density, L_f is the latent heat of fusion, T_m is the freezing temperature of the water, and T_a is air temperature. Equation 1 does not directly account for effects of

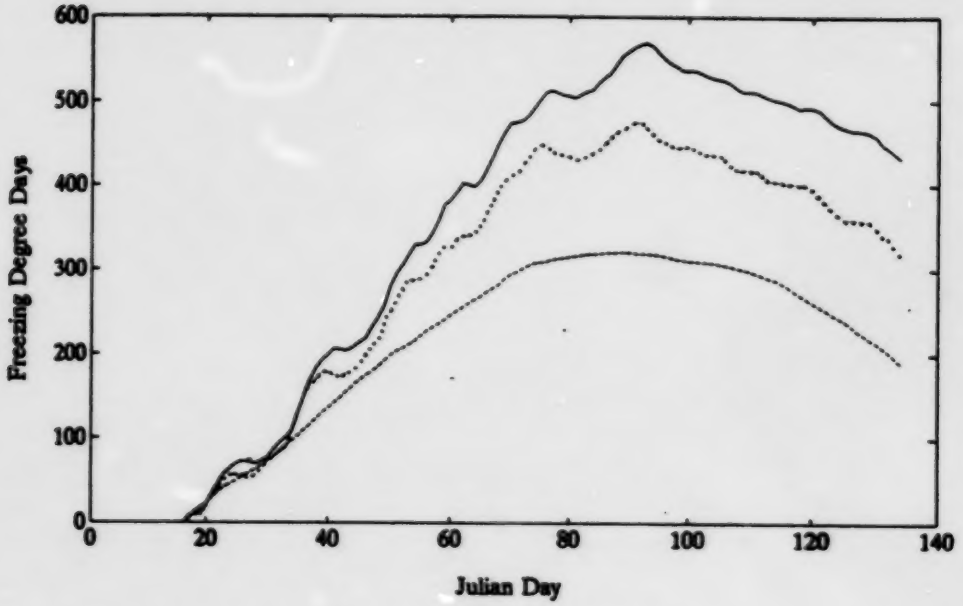


Figure 15. Freezing degree days for Great Mosquito Cove (solid line), Sunnyside 1990 (dotted line), and Sunnyside historical average (dashed line).

snowcover (which can be quite important), but is normally multiplied by an empirical coefficient α which compensates for snowcover and other factors not included in the formula. The constant α is normally found to fall in the range 0.5 to 0.7.

One hundred years later, Ashton (1989) modified the Stefan equation to account for its overprediction of the growth rates of very thin ice. He derived the formula

$$h = \left[\frac{2k_i}{\rho_i L_f}(T_m - T_a)t + \left(\frac{k_i}{H_{ai}}\right)\right]^{\frac{1}{2}} - \frac{k_i}{H_{ai}}, \tag{2}$$

where H_{ai} is an empirically derived bulk heat transfer coefficient ($H_{ai} \approx 10 - 30$ W m^{-2} °C).

A third, and slightly more physically realistic, model was developed by Nakawo and Sinha (1981). In their model, the changes in ice thickness on each day N are summed to give the total ice thickness, that is

$$\sum_1^N (\Delta h_i)_N = \sum_1^N \frac{k_i k_s}{\rho_i L_f} \frac{(T_m - T_a)}{k_i (h_s)_N + k_s (h_i)_{N-1}}, \tag{3}$$

where k_s and h_s are the thermal conductivity and depth of the snow, and Δh_i is the change in ice thickness.

These three models have been run with the measured Great Mosquito Cove air temperatures and the resulting growth predictions are plotted in figure 16. The break-out on about day 50 has been forced, as this is a mechanical rather than thermodynamic process and therefore can not be incorporated into the models. The parameter α in the Stefan equation was set at 0.6, H_{ai} in Ashton's formula was set at 10, and the snow depth and thermal conductivity in the Nakawo and Sinha model were kept constant at 2 cm and 0.25 W m^{-1} °C. In all three models the density of ice was 900 kg m^{-3}, the thermal conductivity of ice was 2.2 W m^{-1} °C, the latent heat of fusion was 3.33×10^5 J kg^{-1},and T_m was 0 °C. Also shown are the measured ice thicknesses (asterisks's). Clearly all three models do a reasonable job, although they do seem to under predict growth in the early stages. In the absence of more detailed time histories of ice thickness, no one model can be said to be particularly better than another. We will therefore select the Nakawo and Sinha (1981) model for the hindcasting studies, simply because

it accounts for the effects of snowcover in a more realistic fashion than the first two formulae.

In predicting the 1990 ice conditions the observed break-out at about day 50 has been explicitly forced, as the thermodynamic model can not account for break-out processes, which are complex functions of ice, oceanic and atmospheric conditions (particularly winds). This shortcoming presents a problem when we try and hindcast ice conditions over the past 17 years. Frequent break-outs are possible even on the coldest years, and can strongly influence the ice regime. Because of the complexities of the breakup processes, attempts at modelling them are unlikely to produce meaningful results. In this case we will not include these affects in the modelling study, but will consider qualitatively what their effects on ice conditions might be.

In order to estimate what ice conditions might be like in both an extremely cold winter, and an extremely warm winter, the Sunnyside temperature records were examined for the period beginning on January 1 and ending on March 31. The warmest year was clearly 1981, when the mean temperature over this three month interval was -1.6 °C. Three winters stand out as being particularly cold; 1974, 1975, and 1990. Although 1975 was the coldest, we will use the 1990 data as the differences between them are not large, and we are fortunate enough to have observations of actual ice conditions during this season.

As mentioned previously, mid-winter break-out events can radically alter the general character of the ice regime. To look at some of the potential effects of break-outs, the thermodynamic model has been run in two configurations. In the first, it is assumed that once an ice cover has formed it does not break out. In the second, break-outs are assumed to occur at regular intervals of 14 days. The freeze up date is in all cases January 15; the observed date of freeze up in the 1990 season. Figure 17 shows the predicted ice growth curves for the 'cold winter' scenario.

The model indicates that climatologically it is conceivable that a fast ice cover of up to 0.6 m could be formed in Great Mosquito Cove. This would require optimal conditions for ice growth, including; low air temperatures, little or no snow, and light winds (and therefore no break-outs). However, if such an ice cover were to form, it would grow increasingly resistant to breakup,

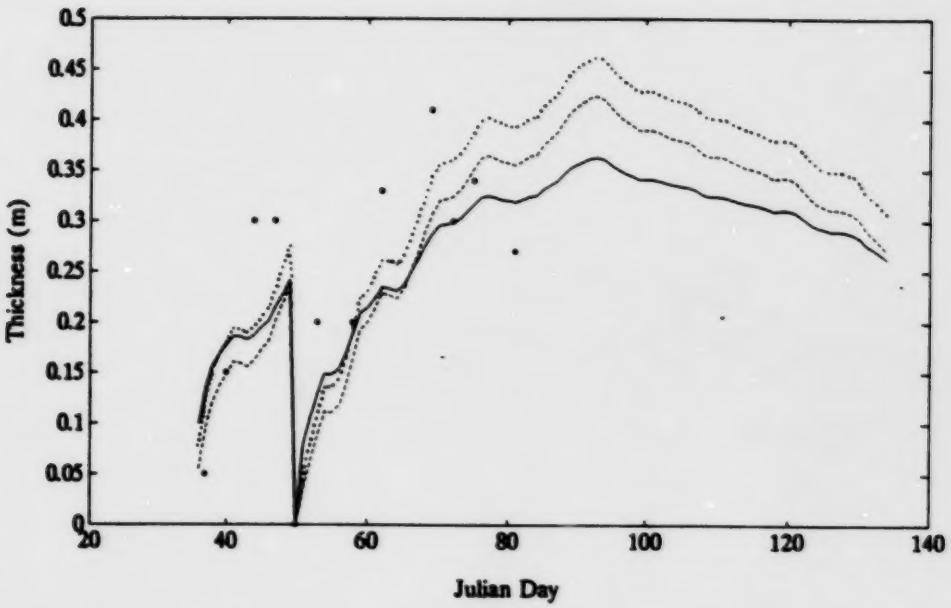


Figure 16. Ice growth in Great Mosquito Cove during the 1990 season modelled using the Stefan model (solid line), Nakawo and Sinha model (dotted line), and Ashton model (dashed line). The asterisks indicate measured ice thicknesses.

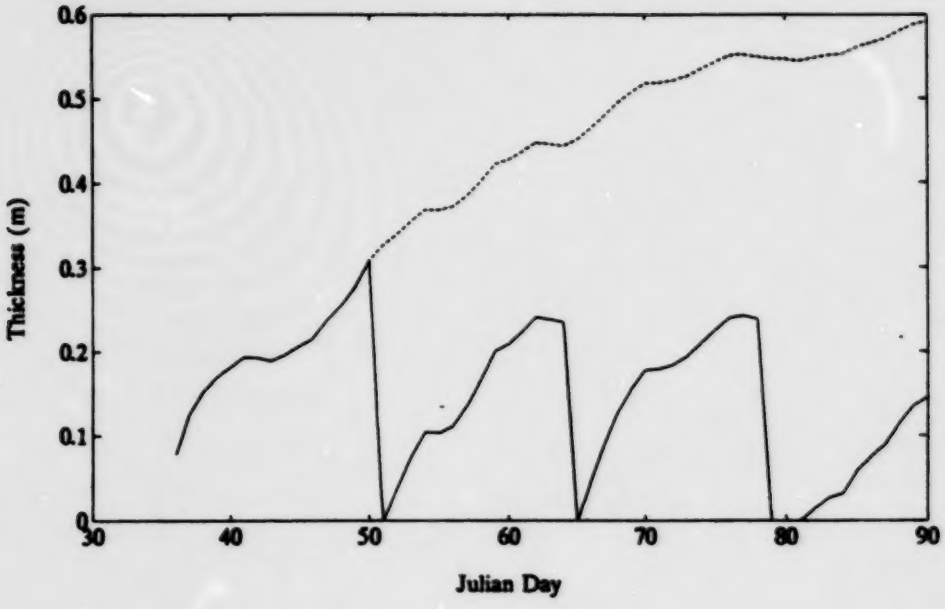


Figure 17. Modelled ice growth in Great Mosquito Cove for the 'cold winter' scenario with no break-outs (dashed line), and with a forced break-out every 14 days (solid line).

and could present a significant obstacle to the development and construction activities. If winds resulted in frequent break-outs, a maximum thickness of just over 0.3 m would result. This is similar to the 1990 conditions, where low air temperatures and a single break-out resulted in maximum thicknesses of about 0.4 m.

The 'warm winter' scenario is shown in figure 18. Here the peak ice thickness, even without break-out events, is approximately 0.2 m. It is highly unlikely that a stable ice cover would survive intact under these conditions, even in the most sheltered portions of the cove. In fact, in a warm winter such as this, the water column may not cool sufficiently for even a thin skim of ice to form and persist for more than a few hours or days.

Figure 19 shows ice conditions predicted using the observed mean temperatures. Even the unlikely event of a year with no break-outs, the peak ice thickness in this case would be less than 0.4 m. The data suggest that in a winter where some break-out events do occur, a strcuturally sound ice sheet is unlikely to develop.

Because it is the severe winters, with the heavy ice conditions, which are of greatest concern in the design and operation of engineering facilities, it is of interest to know the likelihood of ice conditions similar to those observed in 1990 recurring during the planned development and construction period. Although historical ice records are not available for this area, it is possible to look at the probability of recurrence of atmospheric conditions similar to those which produced the heavy ice cover of 1990.

To accomplish this, the general form of the temperature probability distribution must first be established. Because there are only seventeen years of temperature data for the Sunnyside station (which is an insufficient quantity for determining spectral shape), we used the St. John's airport data which covers a period of 47 years, and assumed that the distributions are similar. A quick look at the mean St. John's temperatures over the January 1 to March 31 period suggests that a gamma probability distribution might be appropriate. The general form of the gamma distribution is

$$f(x) = \frac{1}{\Gamma(c)b^c}\, x^{c-1} \exp(-x/b) \qquad (4)$$

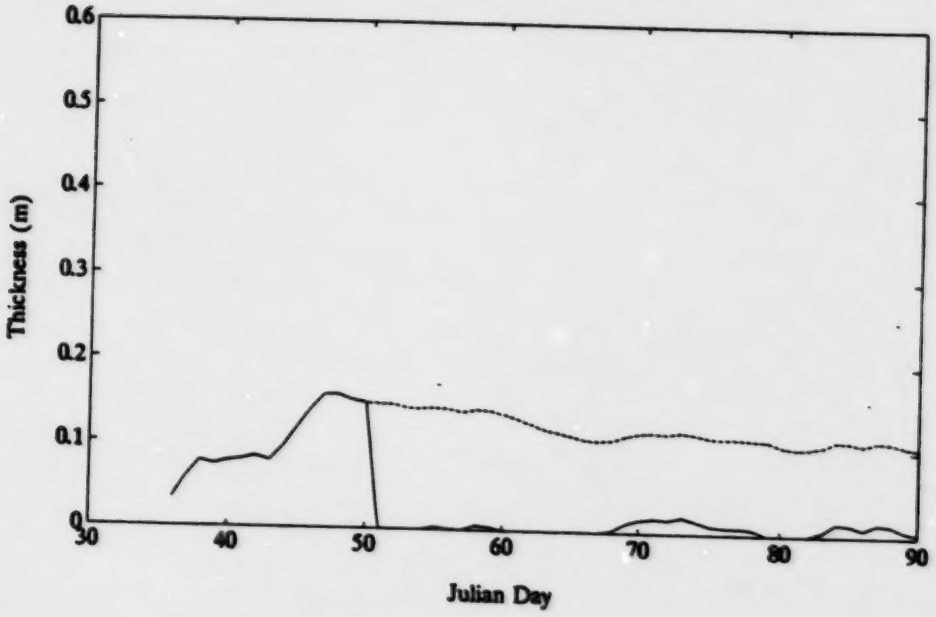


Figure 18. Modelled ice growth in Great Mosquito Cove for the 'warm winter' scenario with no break-outs (dashed line) and with a forced break-out every 14 days (solid line).

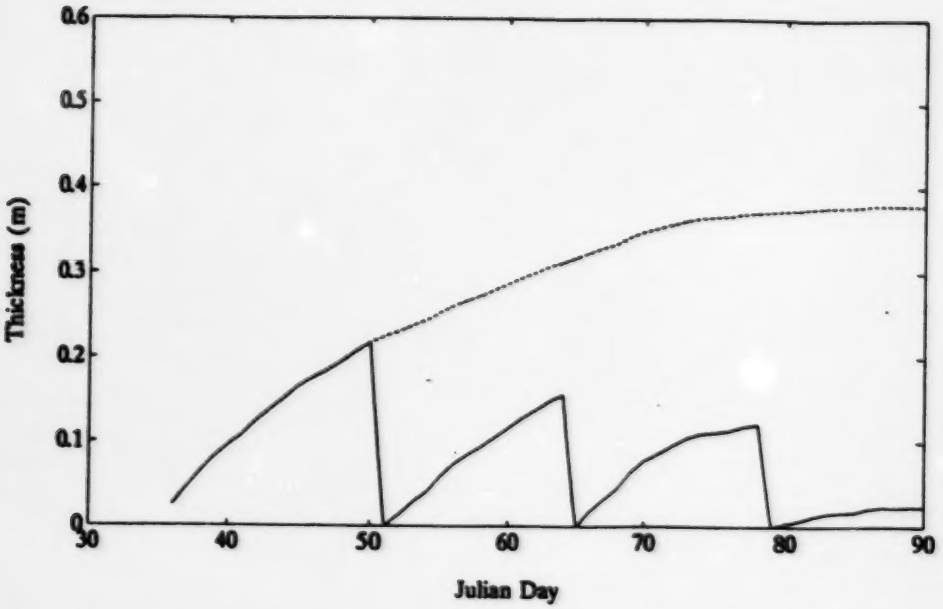


Figure 19. Modelled ice growth in Great Mosquito Cove for the 'mean winter' scenario with no break-outs (dashed line) and with a forced break-out every 14 days (solid line).

where

$$\Gamma(c) = \int_0^\infty \exp(-u)u^{c-1}\, du, \tag{5}$$

c is a shape parameter and b is a scale parameter. The shape and scale parameters can be estimated using

$$b \simeq s^2/\overline{x}, \tag{6}$$

and

$$c \simeq (\overline{x}/s)^2, \tag{7}$$

where $\overline{x}$ and s are the mean and standard deviation respectively. Since equation 4 is valid only for values of x greater than 0, we will use negative temperature (degrees Celsius) and produce a mirror image of the actual temperature distribution. The mean temperature for the 47 years of St. John's data is -3.7 °C ($+3.7$ in the distribution calculations), and the standard deviation is 1.40 °C. This gives values of b and c of roughly 0.53 and 7.0 respectively. Figure 20 shows the probability distribution for the measured temperature data (grouped into 1 °C bins) and the distribution calculated using the gamma function. The fit is reasonably good considering the small sample size, and we will assume that a similar distribution will accurately represent the Sunnyside/Great Mosquito Cove region.

In order to make the calculated distribution more representative of the Sunnyside area, a curve is chosen with the same shape parameter ($c = 7$), but with the scale parameter altered to reflect the lower mean temperature (-4.9 °C). This gives a value for b of 0.70, and a distribution as shown in figure 21. Also plotted in this figure are the grouped, measured Sunnyside data. Given the very small sample size of 17 years, it is not surprising that the fit is not quite as good as that obtained with the St. John's data. However, the gamma distribution stills appears to reflect the general pattern reasonably well, and we can use it to estimate the likelihood of any specific mean temperature occurring in any one year.

Exceedence probabilities can either be estimated from figure 21, or calculated using

$$P(x \geq n) = f(n) = \sum_{k=0}^{c-1} \exp(-n/b)\frac{(n/b)^k}{k!} \tag{8}$$

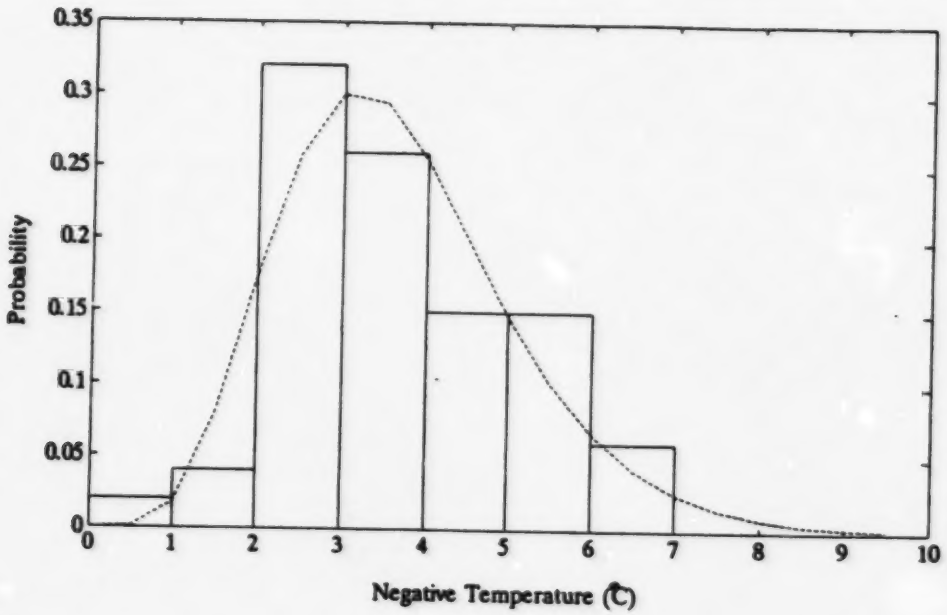


Figure 20. Probability histogram of St. John's mean temperature from January 1 to March 31 (47 years of records), and the modelled gamma distribution (dashed line).

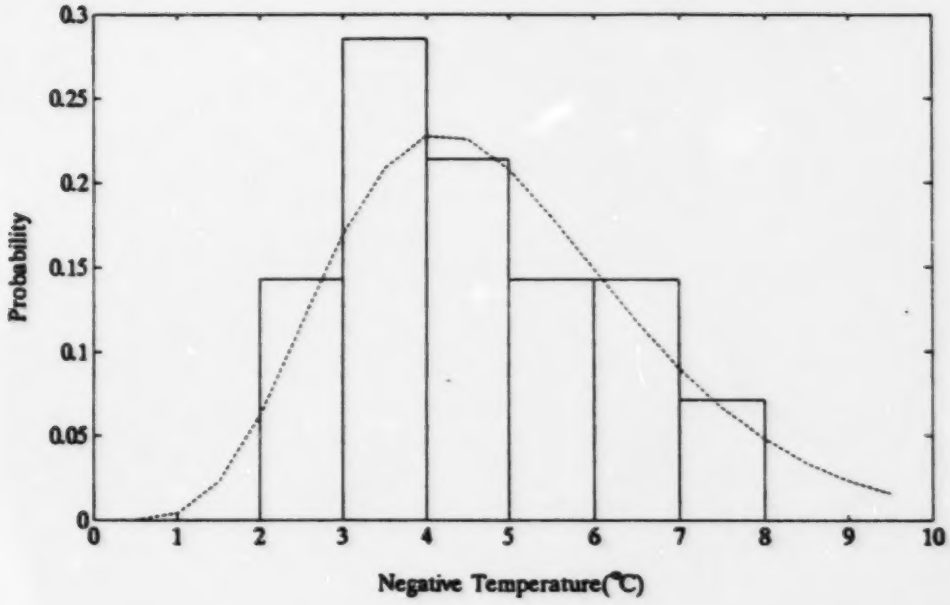


Figure 21. Probability histogram of Sunnyside mean temperature from January 1 to March 31 (17 years of data), and the modelled gamma distribution (dashed line).

where n is an integer representing the exceedence temperature. For example, the heavy ice year of 1990 occurred with a mean January through March temperature of approximately -7.5 °C. The probability of temperatures between -7.0 and -8.0 occuring in any given year is 0.067. In other words, mean temperatures in this range are likely to occur once every 15 years. The probability of mean temperatures less than -7.0 °C occuring in any given year is from equation 8, equal to 0.13, a return period of about 7 years.

Although air temperature is the most important variable controlling ice conditions, it is not the only factor involved. Linking the probability of specific temperatures to the probability of specific ice conditions is tenuous at best. Winds, oceanic conditions (currents, temperatures, waves etc.), insolation, snowcover, and many other factors are also important. There is the question of stationarity as well. In the preceeding analyses it is implicit that there is no trend in the mean temperature. On a time scale of a few decades this is unlikely to be the case. The historical record clearly shows temperature fluctuations, and there is some inconclusive evidence indicating a warming trend will occur over the next several decades. The Sunnyside temperature record shows that the mean temperature during the January 1 to March 31 period was about 1 °C cooler in the 1970's than in the 1980's. Such a trend would make the calculated probabilities of extremely cold winters too large. However, in the complete absence of any historical ice data, this is our only recourse, and a relationship between mean air temperature and ice conditions will be assumed, but should be viewed with an appropriate degree of caution.

3.3 Local Knowledge

The second approach to determining historical ice conditions is to utilize the personal knowledge of people who have lived in the area for many years. This is a tremendous source of information, but is often difficult to obtain and even more difficult to interpret. For example, local terminology often varies considerably. Problems also arise when people have greatly differing opinions of the severity of ice conditions. Someone who uses the fast ice cover as a winter road, will have a greatly different opinion of a 'heavy' ice year than someone who wants to get their boat in and out of the harbour. Nevertheless, local knowledge should not be overlooked.

The approach used in this study was personal interviews of senior members of the community of Sunnyside. A questionnaire was drawn up (see Appendix C) and used as a guide in the interviews. It was, however, only used as a guide, and individual interviews were allowed to take any form conducive to the extraction of the desired information. The interviews were conducted by Denny Christian of C-CORE on June 28, 1990. Although it was originally planned that about ten persons would be consulted, only five interviews actually took place. This was because the responses to the questions were so consistent that additional consultations were deemed unnecessary. The selection of persons for interview was directed by Bob Drover who lived in Sunnyside and had worked on the ice observations portion of the programme. Some persons were interviewed in their homes whiles others were interviewed on the docks. The primary selection criterion was many years of experience with ice conditions in the area.

The survey produced a wealth of information, which can be summarized as follows. A fast ice cover does not usually form in Great Mosquito Cove. When an ice cover does form, it typically occupies only the inner half of the cove, and lasts for only a few days before breaking out. The earliest reported appearance of fast ice here was January, and the latest occurrence was late April or early May. All respondents reported the thickest ice as being 0.4 m, recorded in 1990. The consistency of this value suggests that this was the figure circulating around the town, and that it was based on only Bob Drover's personal observations. It is unlikely that people routinely measure the thickness of the ice, so this value may not be an accurate extreme ice thickness. All of the persons interviewed said that 1990 was one of the heaviest ice years in memory. One person suggested that it was the heaviest ice to occur in the area in 17 years. This coincides well with the prediction of a 15 year return period for the 1990 air temperatures, as derived in the previous section.

Pack ice also appears in the Bull Arm/ Mosquito Cove area on occasion. Its earliest appearance was reported to be some time in April, while intrusions as late as July can also occur. The extreme maximum thickness of pack ice was reported to be about 1.0 m. In most years no pack ice is observed, the last occurrence being about seven years ago (1983). When pack ice does drift into the cove its residence time can be up to 8 to 10 days.

Icebergs were said to occur very infrequently in this area. When they do appear they tend to be small. Occasionally larger icebergs become grounded outside of Bull Arm, where they may remain for most of the summer.

In general it was indicated that the winter of 1990 was one of the worst (ie. the most ice) for fast ice in many years. It was also suggested that ice conditions are generally less severe now than they were 40 or 50 years ago. There are fewer icebergs in the area now as well. Most people felt that reasons for such heavy fast ice conditions this year was the combination of cold air temperatures, no snow, and very little wind.

4 Discussion

Having established a site specific ice climatology for Great Mosquito Cove, it is interesting to see how conditions at this location compare with general conditions in Trinity Bay. Davidson (1985) provides a summary of ice conditions in all the major bays surrounding the island of Newfoundland, including Trinity Bay. This data was extracted from a variety of sources including SLAR (side looking airborne radar), satellite imagery, ship reports, coastal observation reports, and 'opportunity' surveillance. It covers the period from 1960 through 1984.

One of the more interesting features of the ice distribution on Trinity Bay is its bi-modal nature. Ice is most likely to occur in late February or early March, but there is a secondary peak in the probability of occurence in early May. This coincides well with interview data from Sunnyside, the first peak representing the appearance of fast ice and the second peak corresponding to incursions of pack ice. The minimum fast ice extent in Trinity Bay is 0 tenths, which supports the modelling conducted in the current study (see figure 18). Also of interest are the median fast ice extent (one tenth), and the maximum fast ice extent which was shown to be about three tenths. The maximum total ice (fast ice and pack ice) concentration is 10 tenths, and the median total ice concentration is three tenths.

Again considering the ice conditions specific to Great Mosquito Cove, the possibility of changes to the ice regime in the near future must be considered. It was mentioned earlier that changes in the regional climate over the next

10 or 20 years may be sufficient to influence ice conditions. Because climatic change is such a complex problem, the likely impacts of a general warming (or cooling) trend on the ice conditions is extremely difficult to predict. Many indicators are suggesting that significant warming may have already begun, but how this might affect local winds, snowfall, ocean currents, and other factors which influence ice growth and decay, is not known. Intuitively, it should result in a general reduction in the length of the ice season and the thickness of the ice which does form. The likelihood of recurrence of conditions similar to those found in 1990 would then be less than the 0.067 suggested in section 3 above.

Additional changes to the ice climatology of Great Mosquito Cove may be brought about by the development itself. Two counteracting processes could conceivably act to modify ice conditions. First, there is the general activity at the site. Frequent movements of vessels into and out of the cove will act to break up the ice cover in its early stages of formation, thereby inhibiting the development of a consolidated ice sheet. Secondly, the construction of piers and/or wharfs in the cove may result in a significant reduction in the exchange of water between Mosquito Cove and Bull Arm/Trinity Bay. This effect would be particularly important in the winter, if an ice sheet were to establish itself. It has been mentioned above that outflow from the streams in the area creates a stratified water column, with a relatively fresh water layer floating above the saline bay water. Because the temperature of maximum density of water with a salinity of less than 24.7 ppt, is above its salinity determined freezing point, brackish water can freeze at the surface while the bulk of the water is above the freezing temperature. At higher salinities the water continues to increase in density as it cools to the freezing point. The cooling of normal ocean water will therefore produce a convective turnover, and the entire mixed layer (which might be tens of metres thick) must be cooled to the freezing temperature before ice can form at the surface. Therefore fresh and brackish water freezes much sooner than sea water, and can grow to greater thicknesses.

Reduced water exchange would exacerbate this problem. Construction of rigid structures in the cove would also act as anchor points for an ice sheet, thereby increasing the wind energy required to induce break-out. These effects would be greatly reduced by frequent breaking of the ice by vessels, or by the operation of bubbler systems, but their potential impacts should

be considered.

5 Conclusions

In most years ice does not form in Great Mosquito Cove. When it does occur it is usually confined to the inner portions of the cove, and is relatively thin (less than 20 cm) and short lived. Occasionally all of the cove and adjacent areas of Bull Arm freeze over completely (as was the case in 1990). The 40 cm of ice observed this season most likely represent the extreme maximum thickness for fast ice in this region. Both the modelling studies and the interviews indicate that the return period for conditions of this severity is approximately 15 years. However, the modelling studies suggest that climatologically, it is possible for an ice cover to grow to a maximum of 60 cm in thickness. This could only occur if all of the environmental factors influencing ice growth were optimal during the same season (that is light winds, cold air, cold water, and little or no snow).

When fast ice forms in Great Mosquito Cove, the initial ice sheet is brackish, with salinities of less than 1 ppt. Subsequent growth at the ice surface and at the base of the ice sheet is quite fresh, generally less than 0.1 ppt. These low salinities lead to low brine volumes, except when the ice is very near to the freezing point. As a result, the mechanical behaviour of the thicker, colder ice will be closer to that of fresh water ice than that of sea ice. The crystal structure is typical of sea ice sheets. The first ice formed is composed of consolidated frazil and/or slush and is fine grained and polycrystalline in nature. The ice formed under this layer is columnar, with the grain sizes gradually increasing with depth as the growth rate slows. It may also have a polycrystalline layer on the surface, formed from the freezing of melted snow or rain water.

Pack ice occasionally drifts as far south as Great Mosquito Cove. The occurrence of pack ice in this area seems to be about once every 10 years. When it does occur, it has a typical thickness of approximately 1 m, and a residence time of up to 8 to 10 days.

Icebergs occur infrequently in Mosquito Cove and Bull Arm. When they do appear they tend to be small. Occasionally large icebergs ground outside

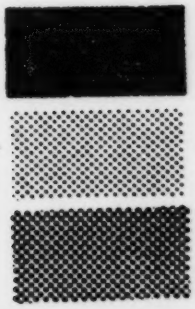
of Bull Arm, where they can remain for most of the summer.

In this report we have attempted to present as broadly based an analysis as possible. No attempt has been made to predict ice loads on any of the engineering structures to be built at the site, or how the ice might help or hinder operations. However, the information has been presented with these types of applications in mind, and should be easily adaptable to any specific engineering problems.

Appendix A

Ice Maps, Great Mosquito Cove, 1990

Figures A1 through A40 show ice conditions in Great Mosquito Cove during the winter of 1990. The symbols used correspond to three different ice thicknesses:



00 - 09 cm (Nilas)

10 - 29 cm (Young Ice)

> 30 cm (First Year Ice)

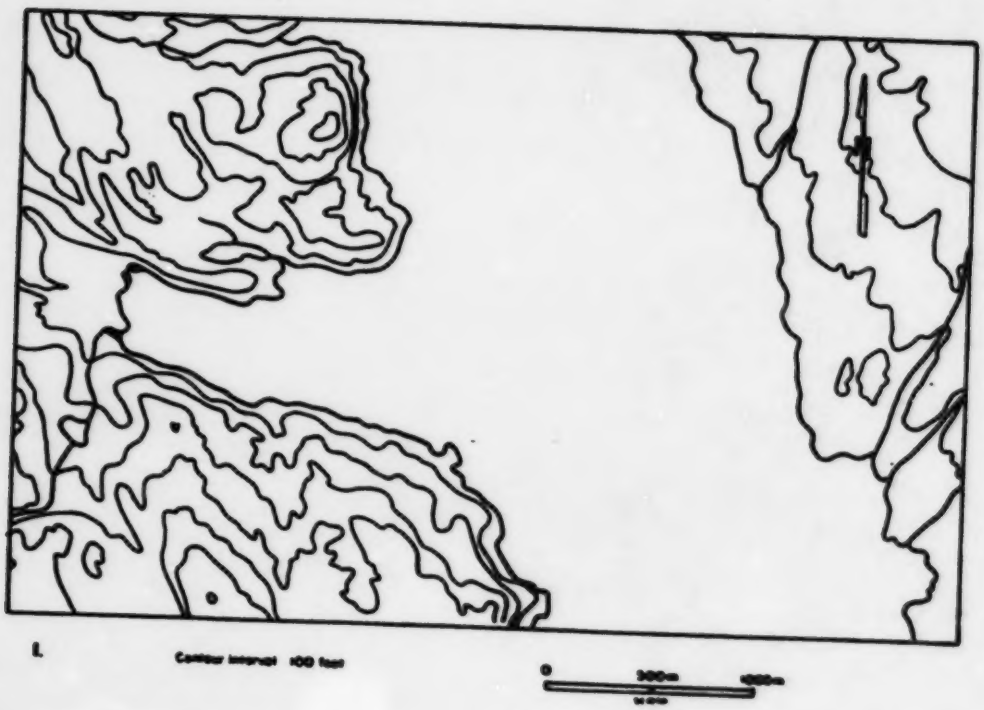


Figure A1 Ice conditions in Great Mosquito Cove, January 10, 1990.

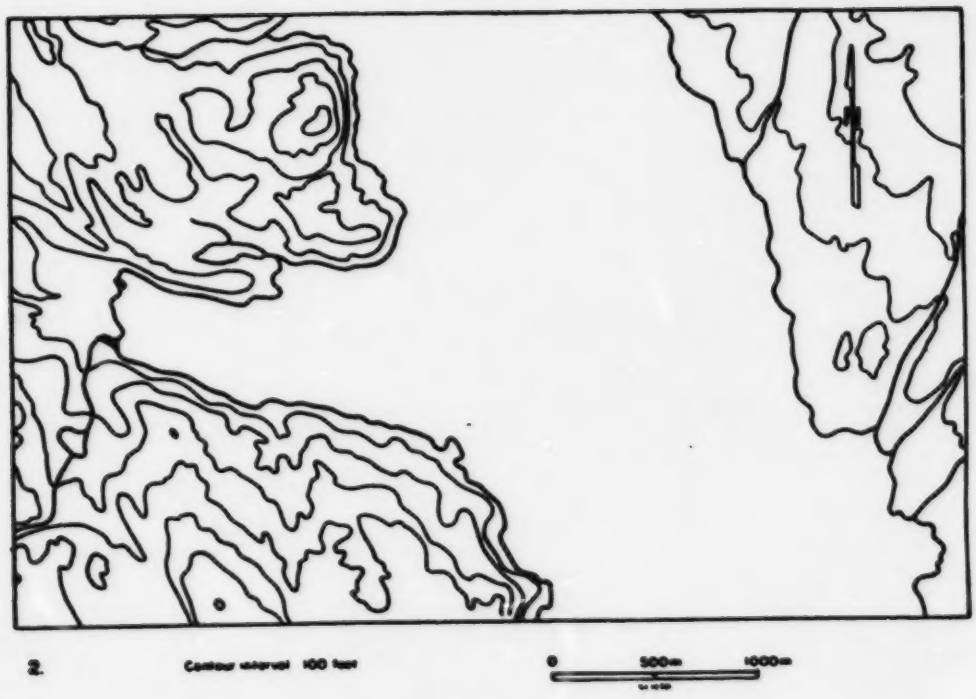


Figure A2 Ice conditions in Great Mosquito Cove, January 15,1990.

Figure A3 Ice conditions in Great Mosquito Cove, January 15, 1990.

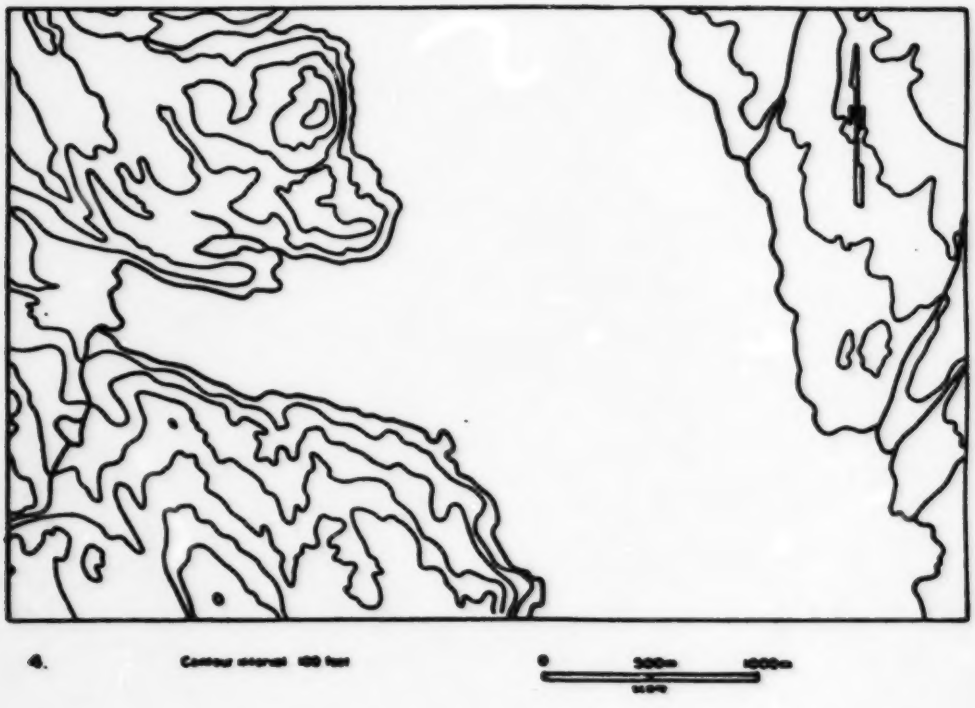


Figure A4 Ice conditions in Great Mosquito Cove, January 20, 1990.

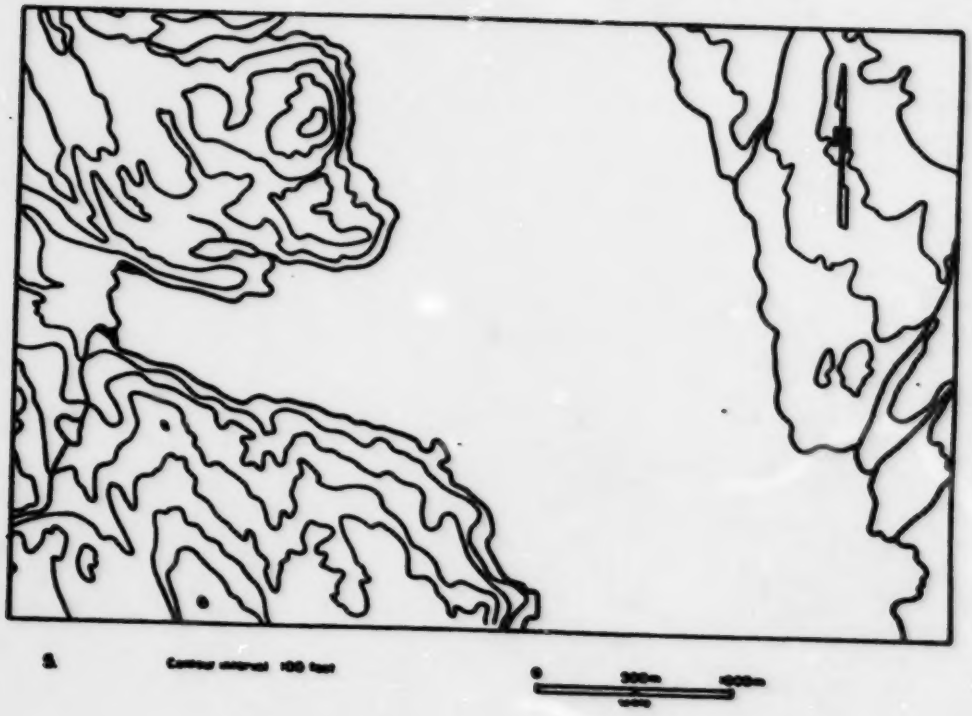


Figure A5 Ice conditions in Great Mosquito Cove, January 22, 1990.

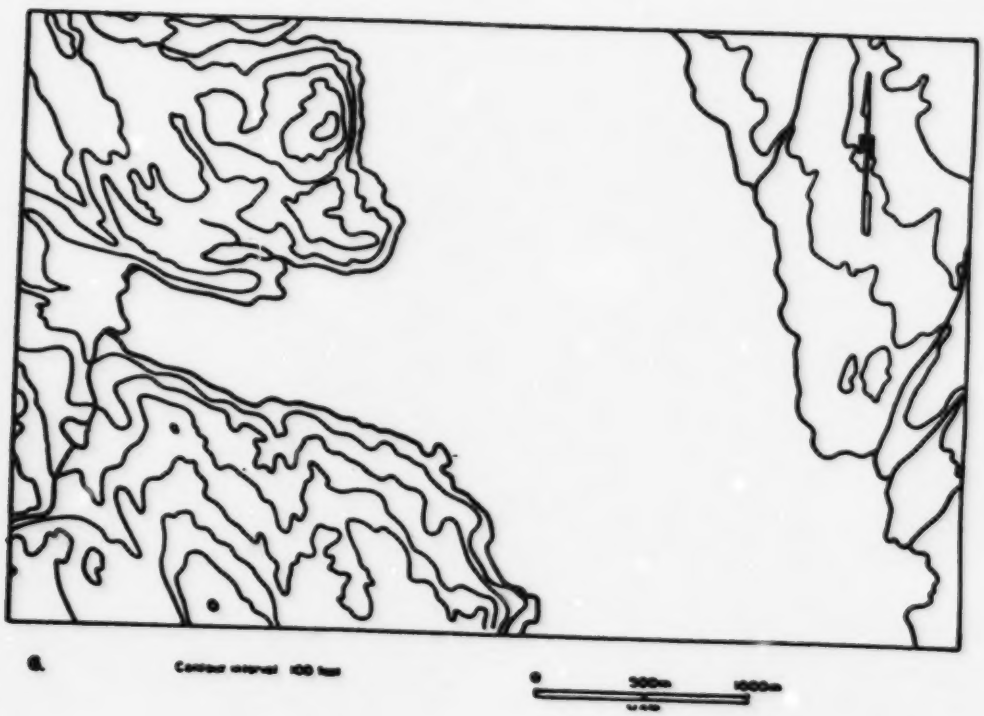


Figure A6 Ice conditions in Great Mosquito Cove, January 23, 1990.

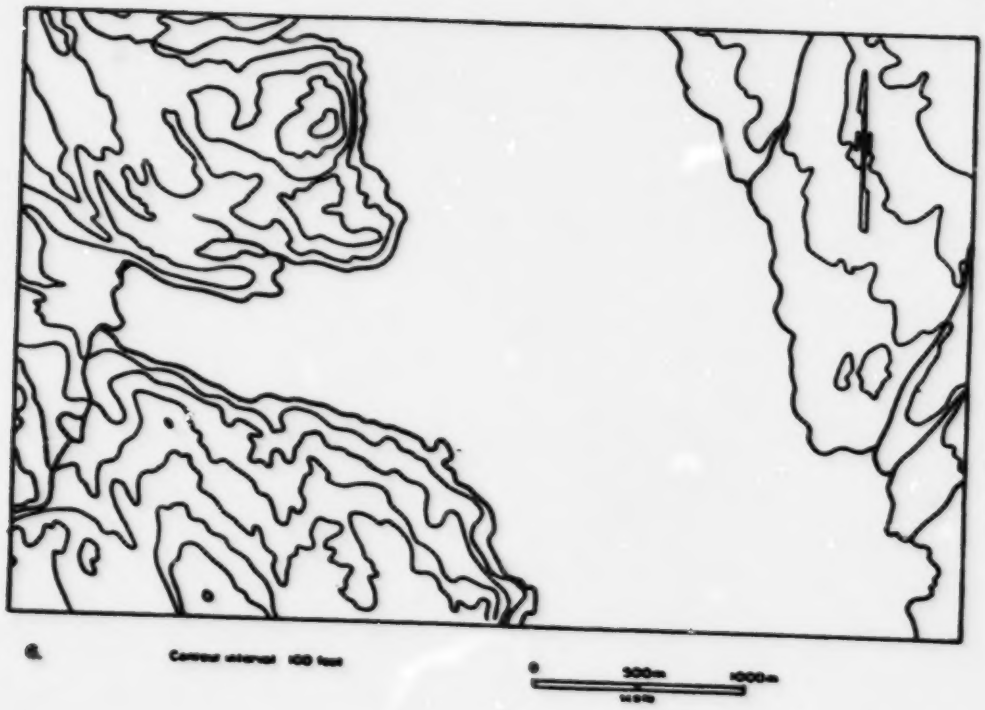


Figure A7 Ice conditions in Great Mosquito Cove, January 26, 1990.

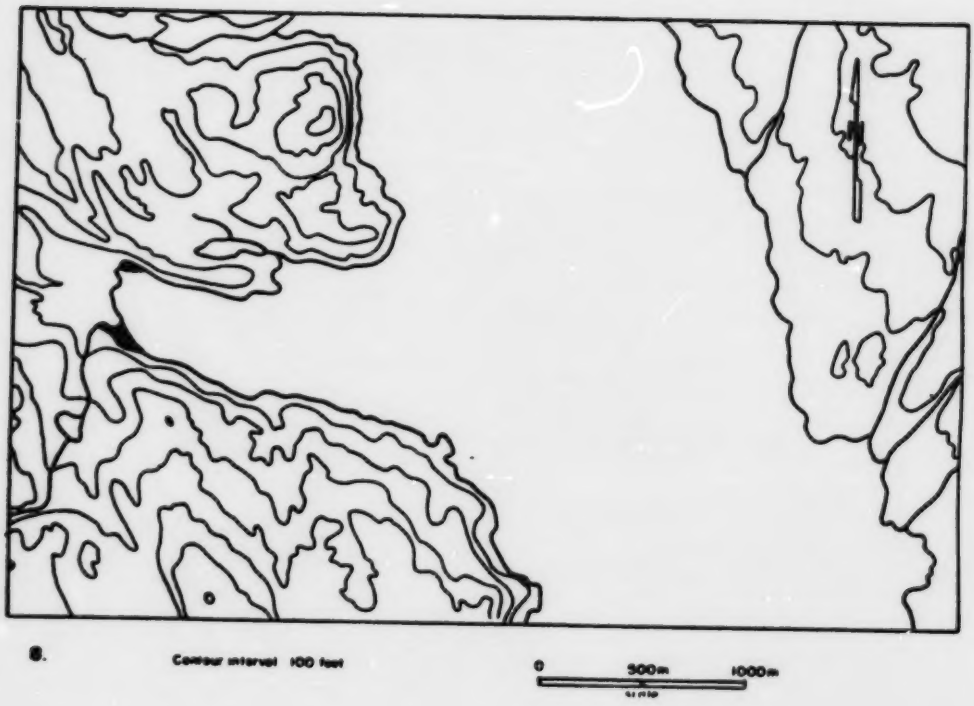


Figure A8 Ice conditions in Great Mosquito Cove, January 30, 1990.

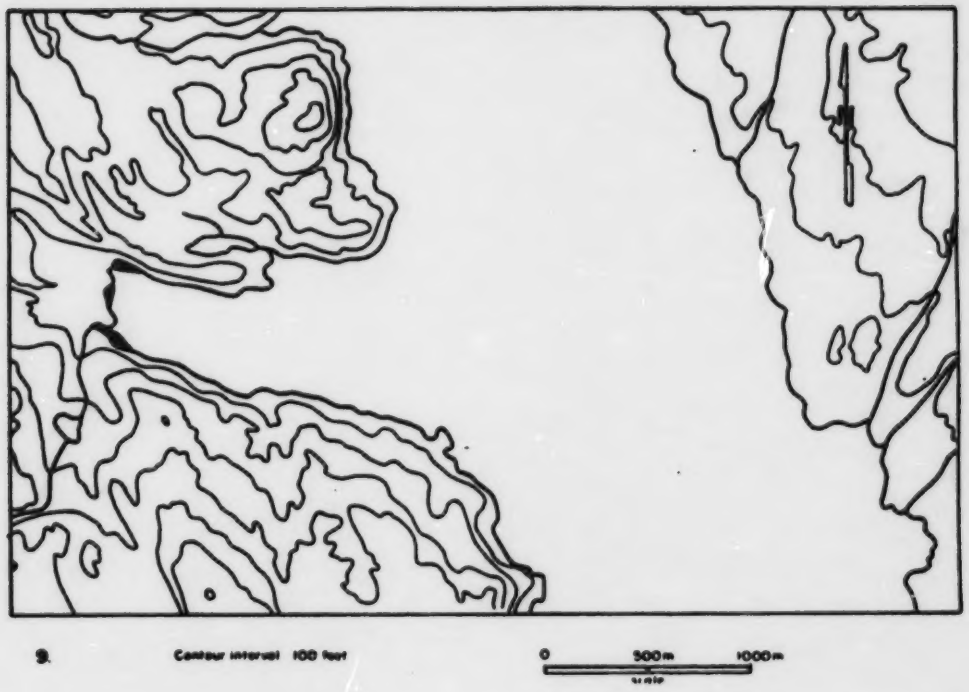


Figure A9 Ice conditions in Great Mosquito Cove, February 3, 1990.

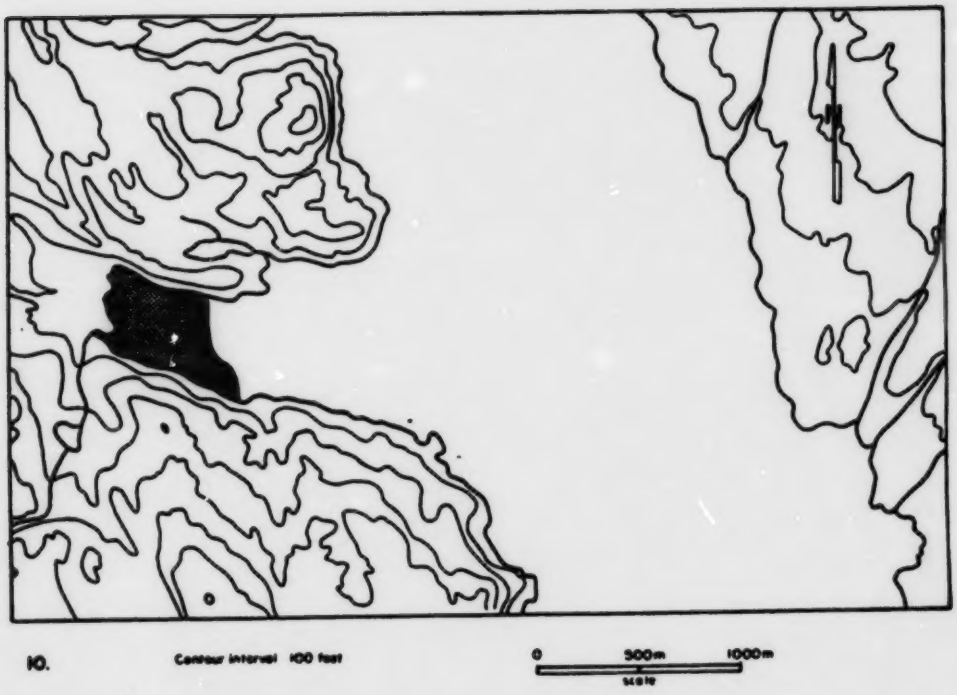


Figure A10 Ice conditions in Great Mosquito Cove, February 6, 1990.

Figure A11 Ice conditions in Great Mosquito Cove, February 6, 1990.

Figure A12 Ice conditions in Great Mosquito Cove, February 9, 1990.

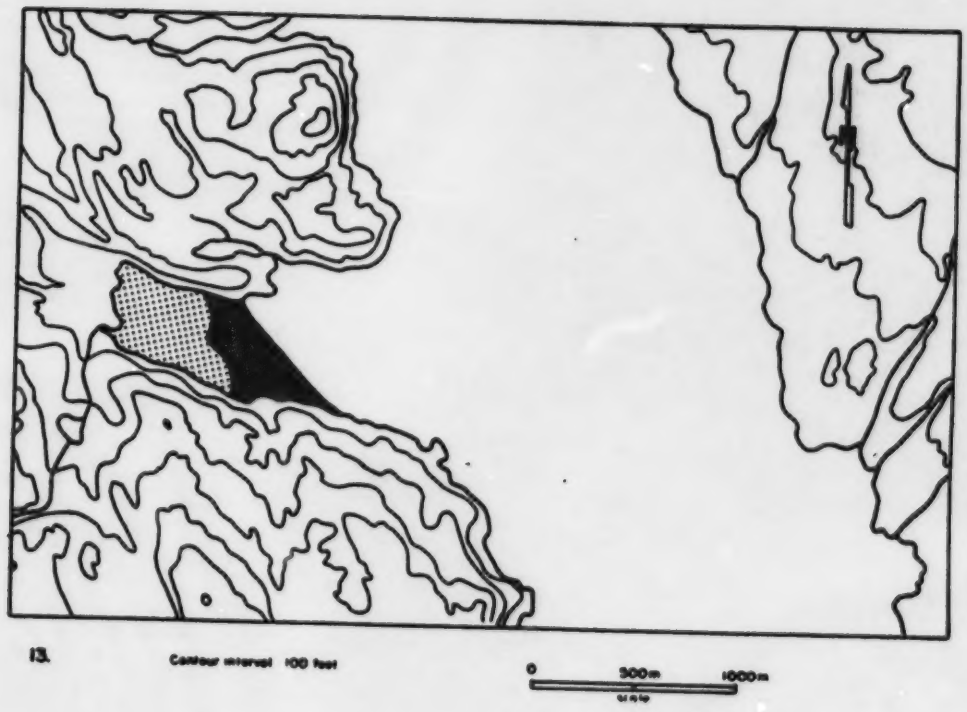


Figure A13 Ice conditions in Great Mosquito Cove, February 13, 1990.

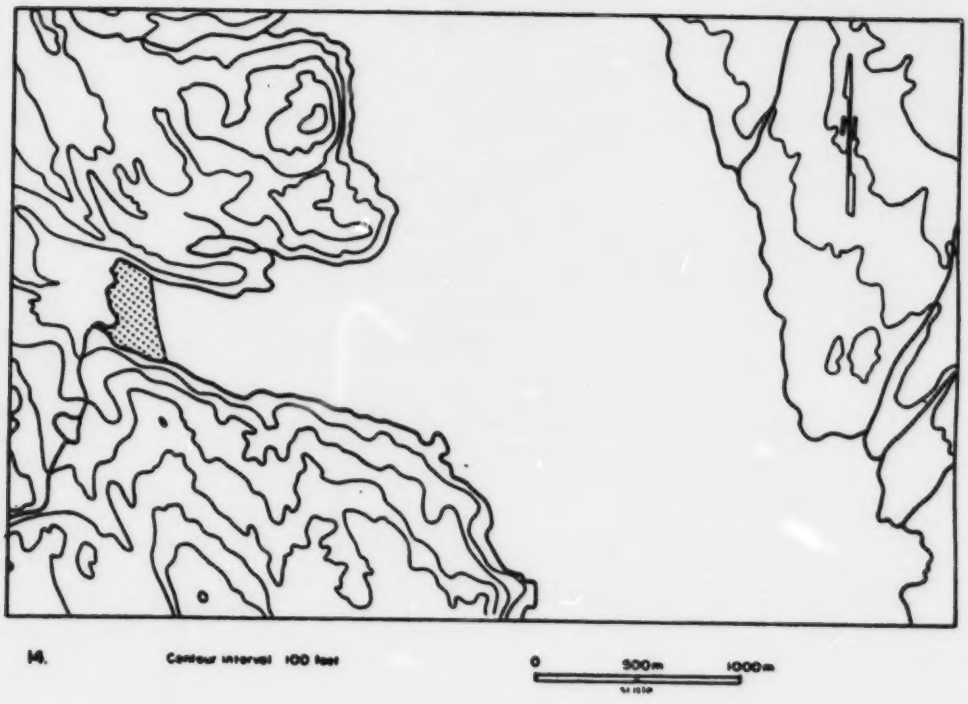


Figure A14 Ice conditions in Great Mosquito Cove, February 16, 1990.

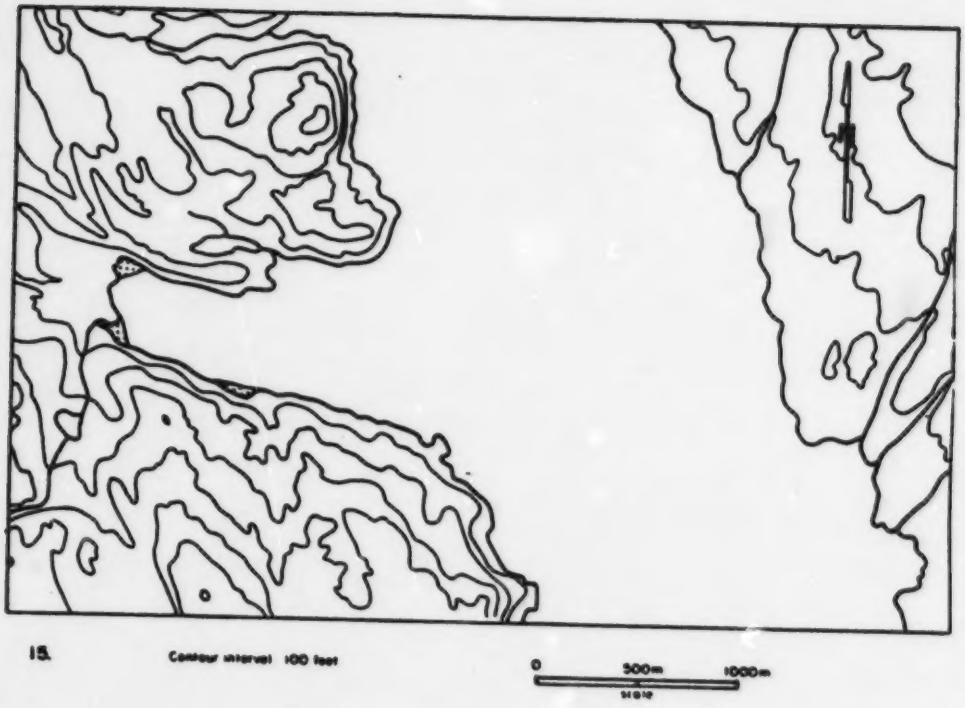


Figure A15 Ice conditions in Great Mosquito Cove, February 19, 1990.

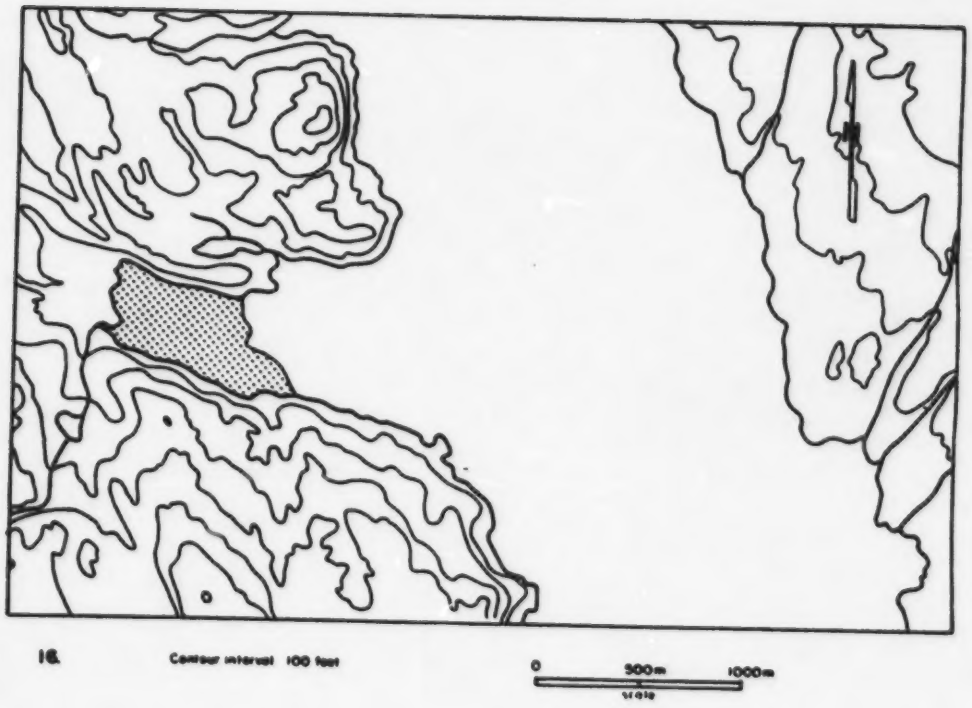


Figure A16 Ice conditions in Great Mosquito Cove, February 23, 1990.

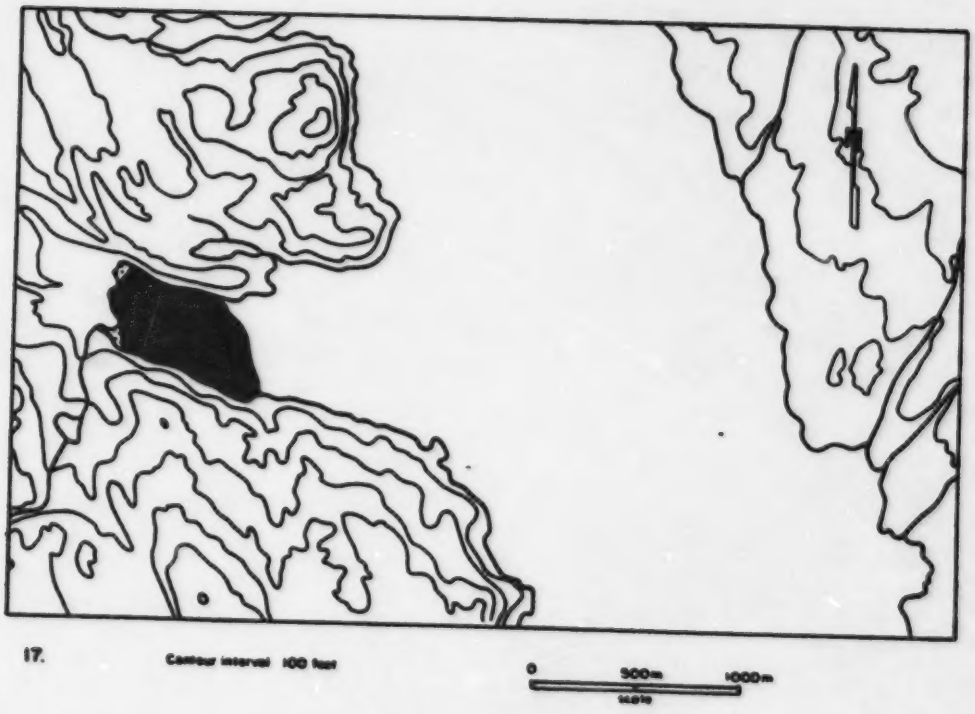


Figure A17 Ice conditions in Great Mosquito Cove, February 24, 1990.

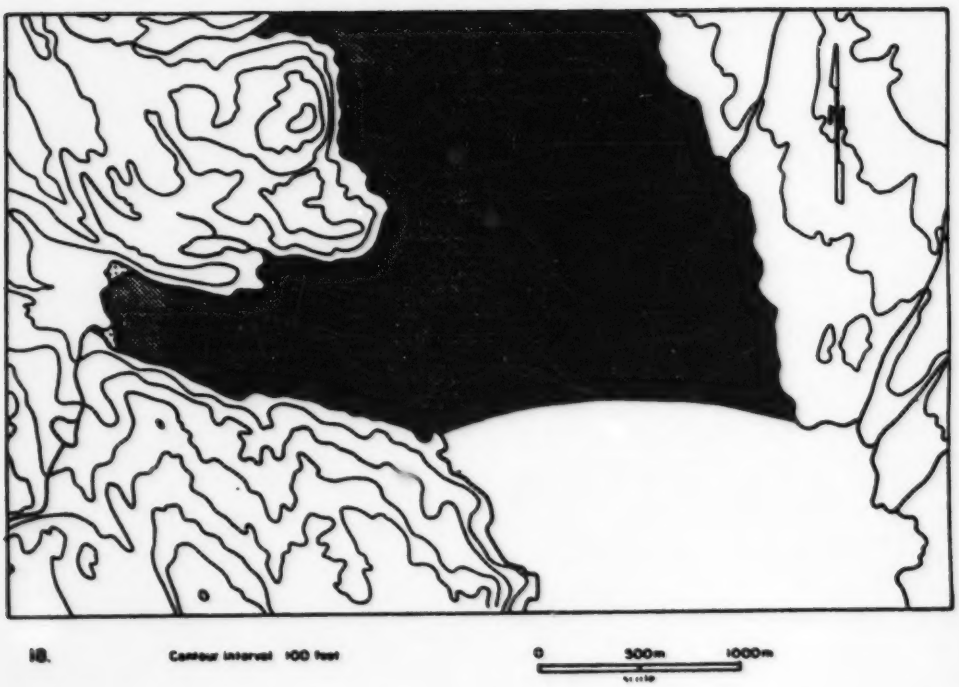


Figure A18 Ice conditions in Great Mosquito Cove, February 27, 1990.

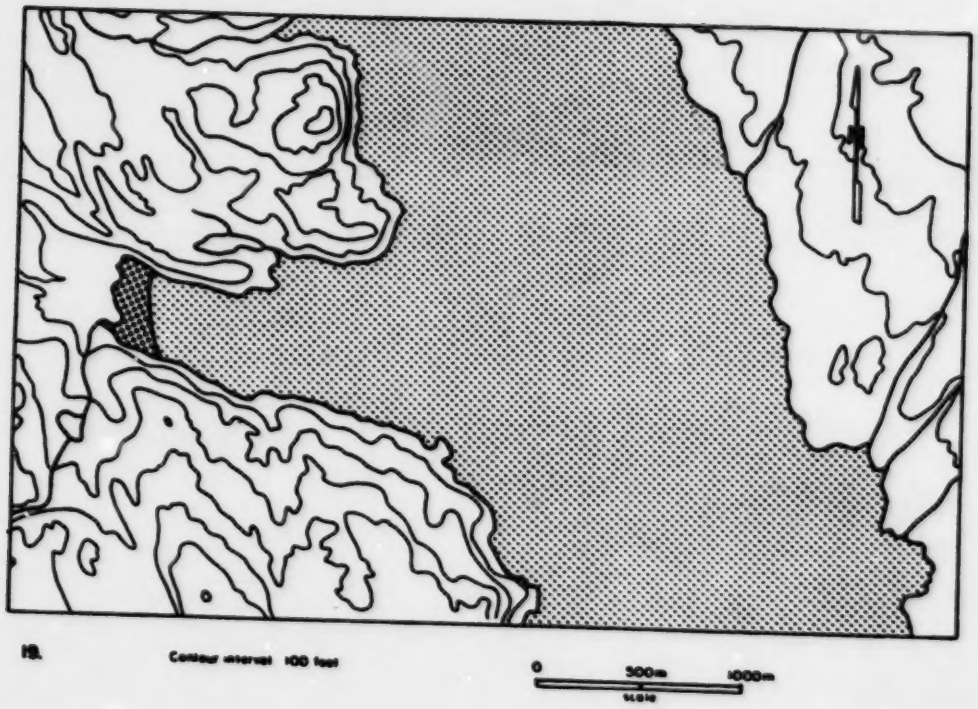


Figure A19 Ice conditions in Great Mosquito Cove, March 3, 1990.

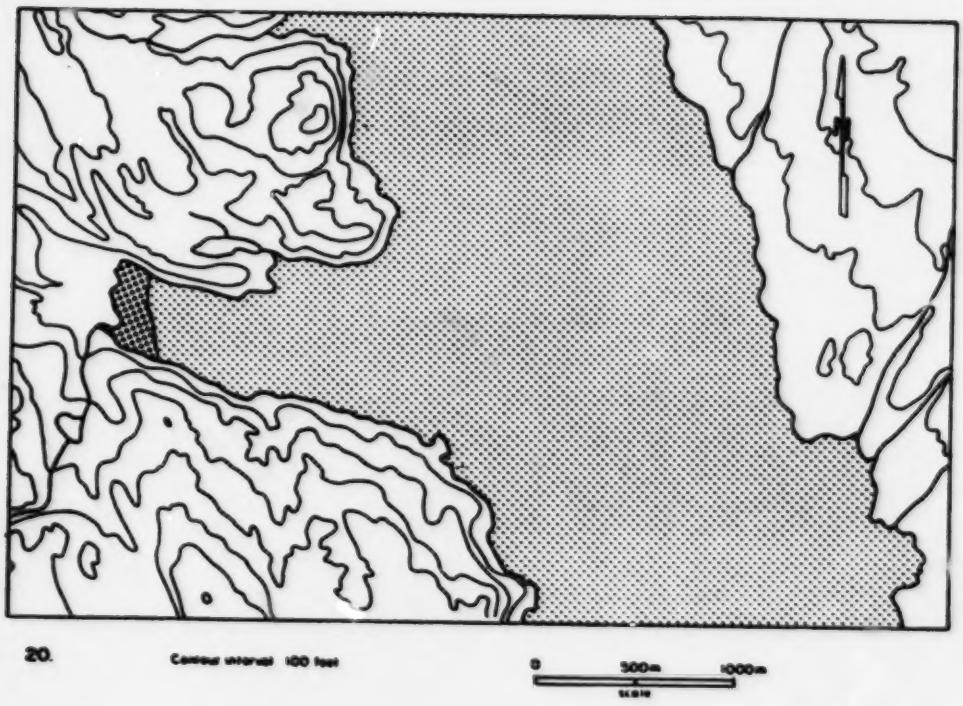


Figure A20 Ice conditions in Great Mosquito Cove, March 6, 1990.

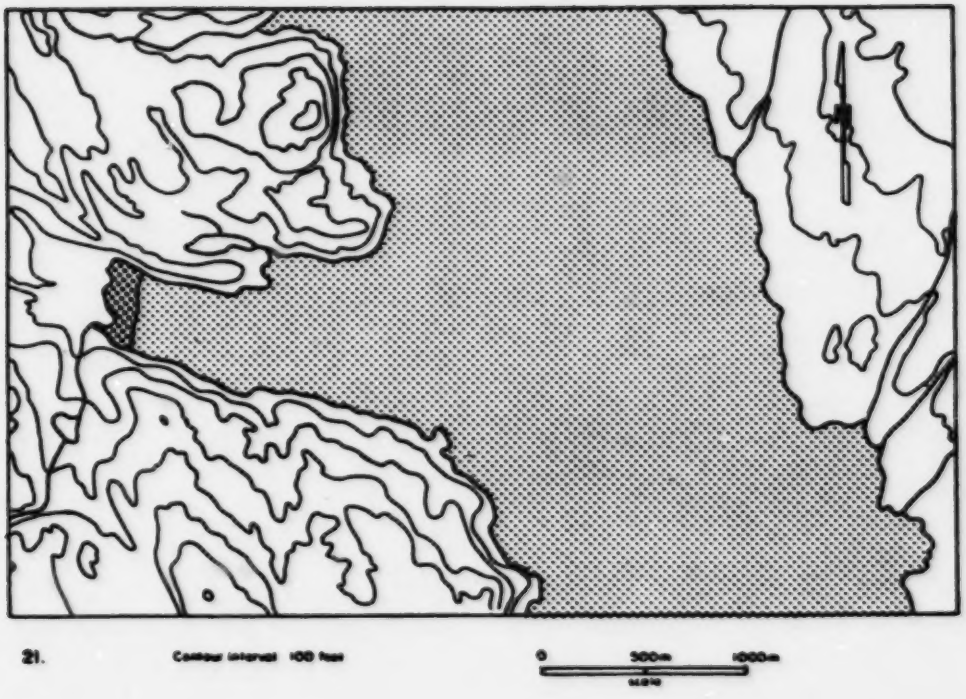


Figure A21 Ice conditions in Great Mosquito Cove, March 10, 1990.

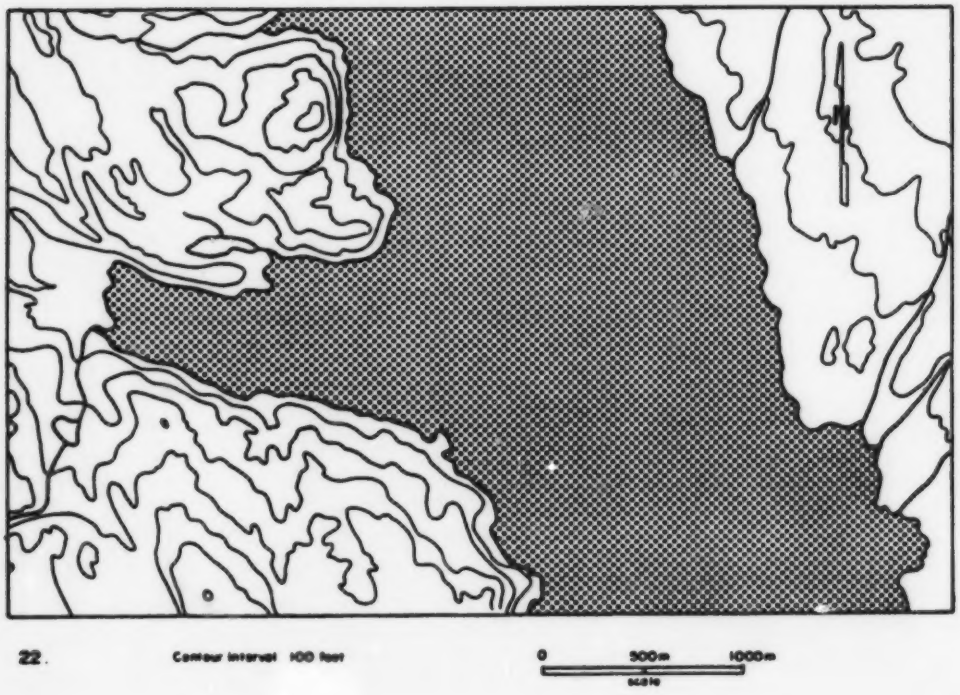


Figure A22 Ice conditions in Great Mosquito Cove, March 13, 1990.

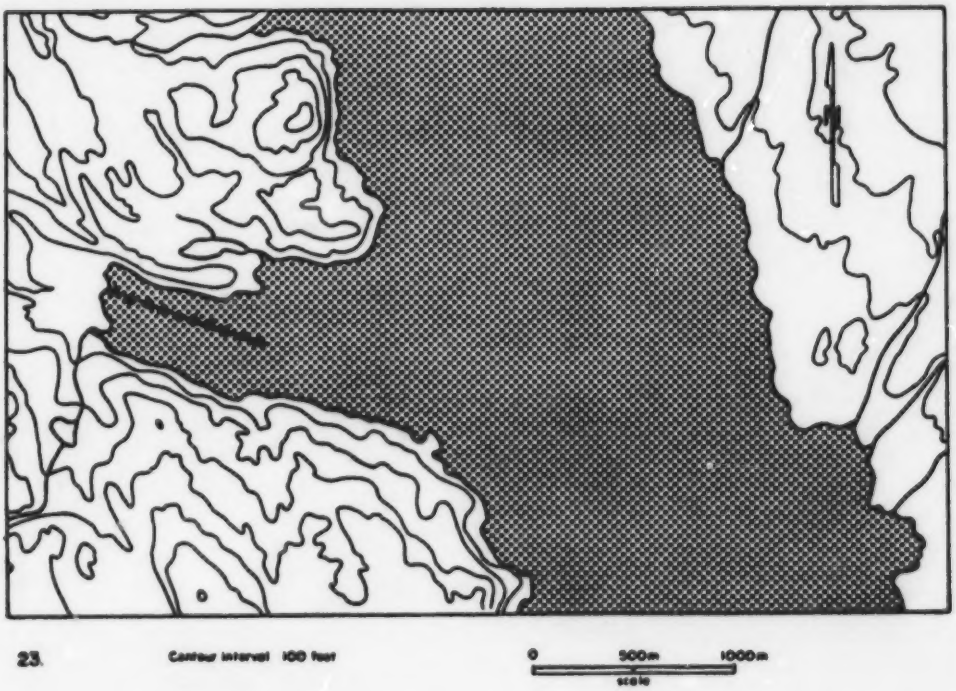


Figure A23 Ice conditions in Great Mosquito Cove, March 13, 1990. The triangles indicate the positions of the ice thickness measurements (see figure 3).

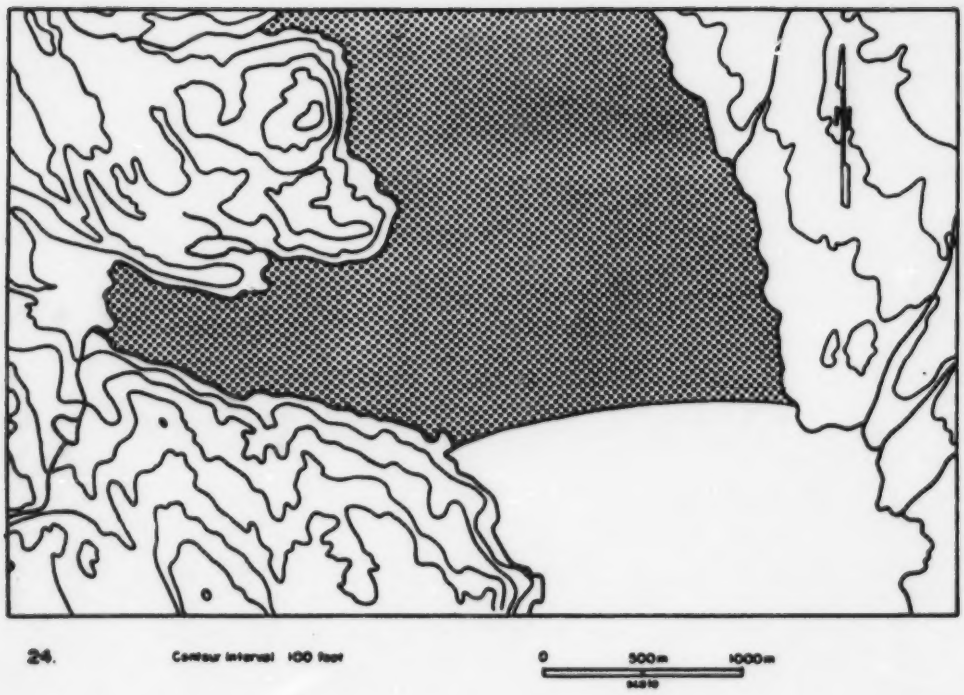


Figure A24 Ice conditions in Great Mosquito Cove, March 16, 1990.

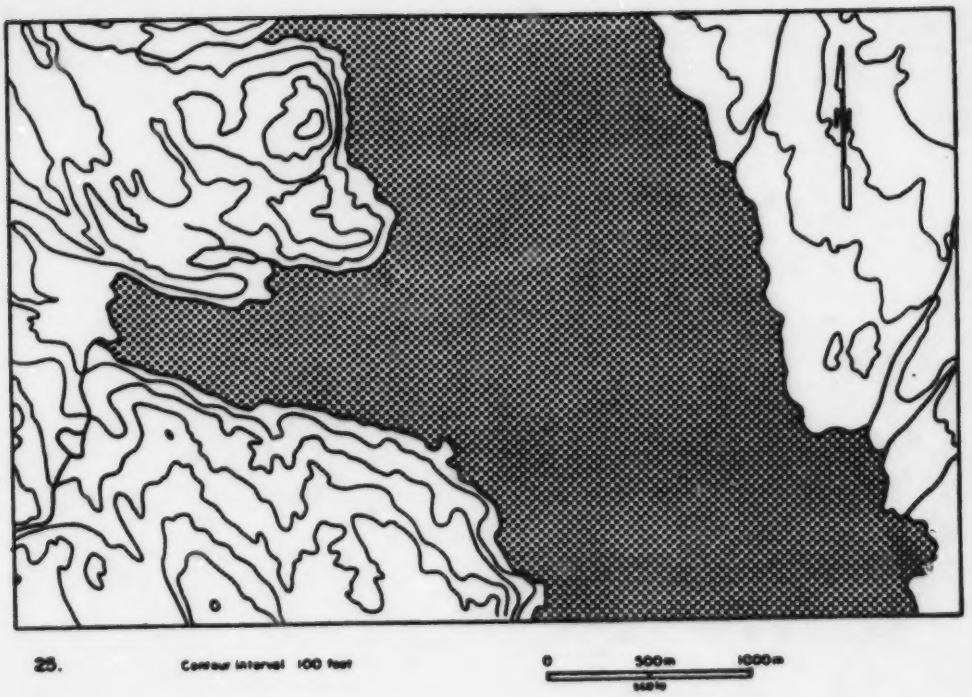


Figure A25 Ice conditions in Great Mosquito Cove, March 19, 1990.

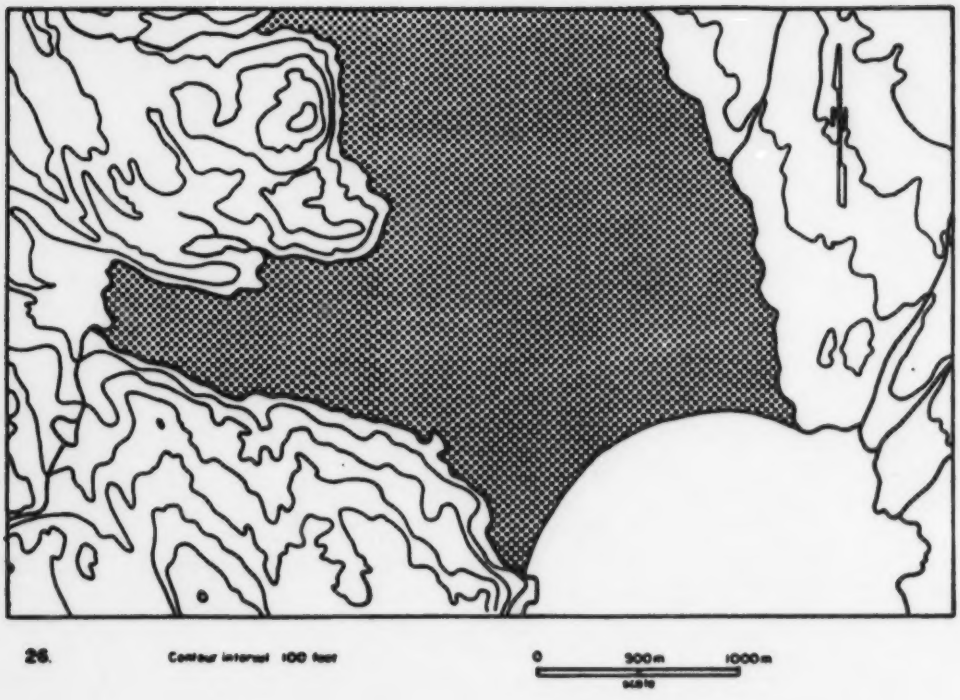


Figure A26 Ice conditions in Great Mosquito Cove, March 22, 1990.

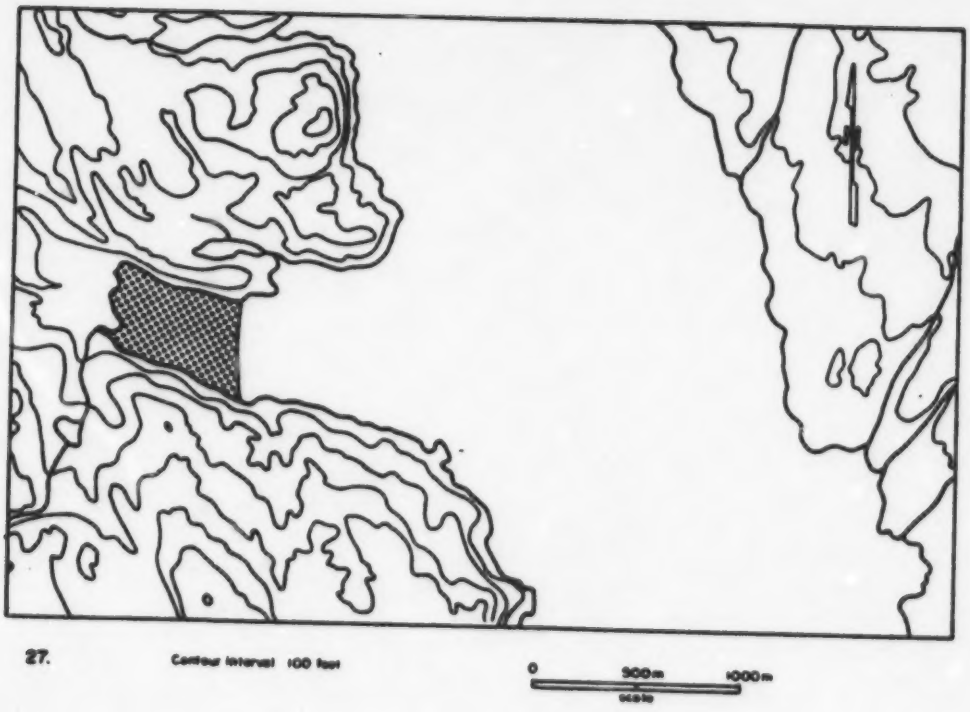


Figure A27 Ice conditions in Great Mosquito Cove, March 24, 1990.

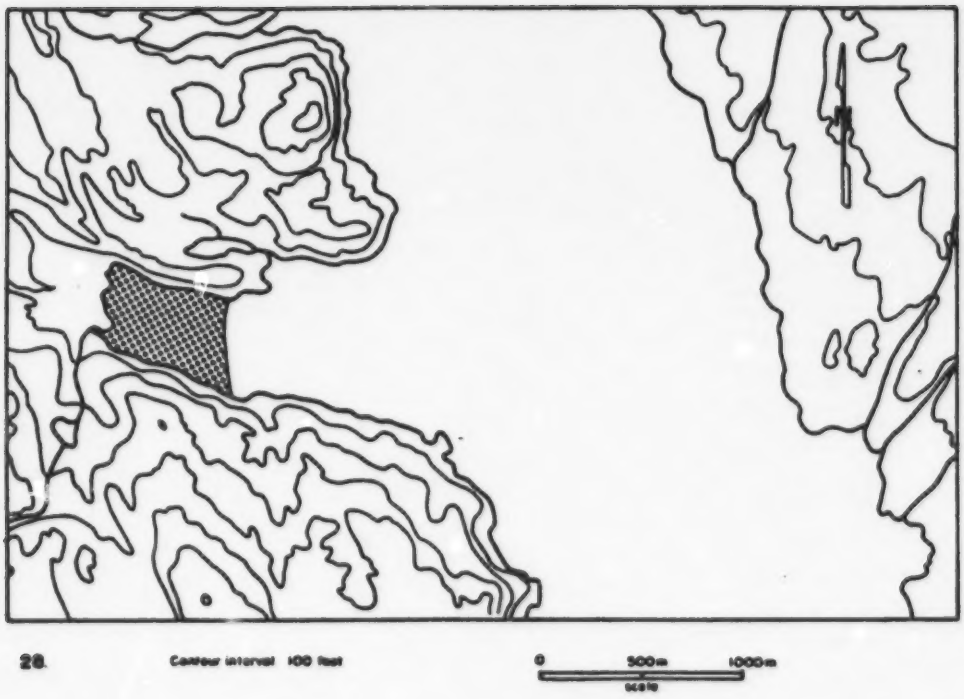


Figure A28 Ice conditions in Great Mosquito Cove, March 27, 1990.

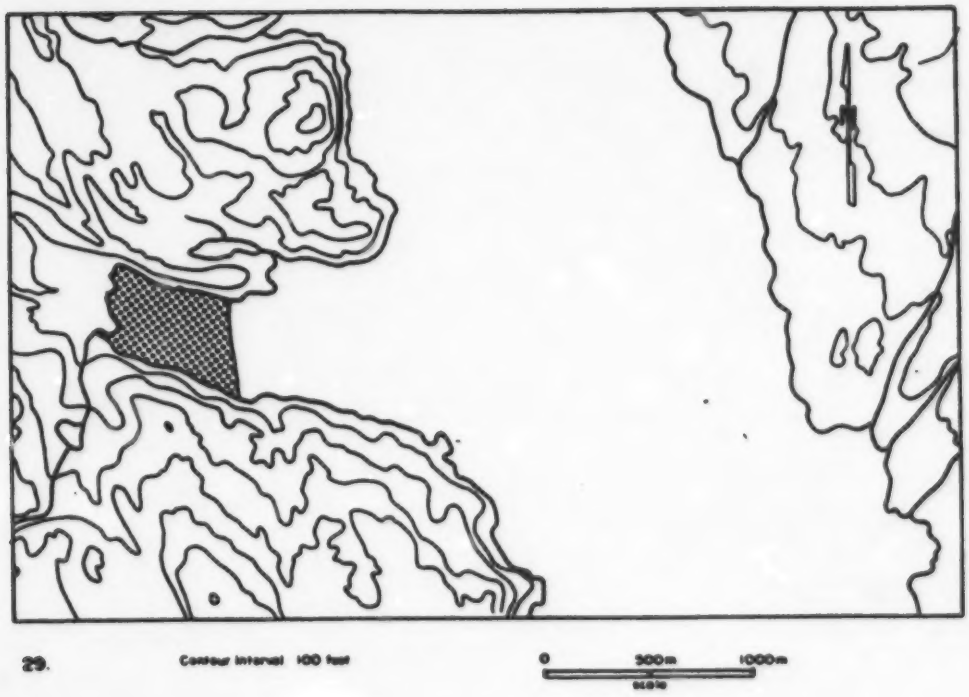


Figure A29 Ice conditions in Great Mosquito Cove, March 31, 1990.

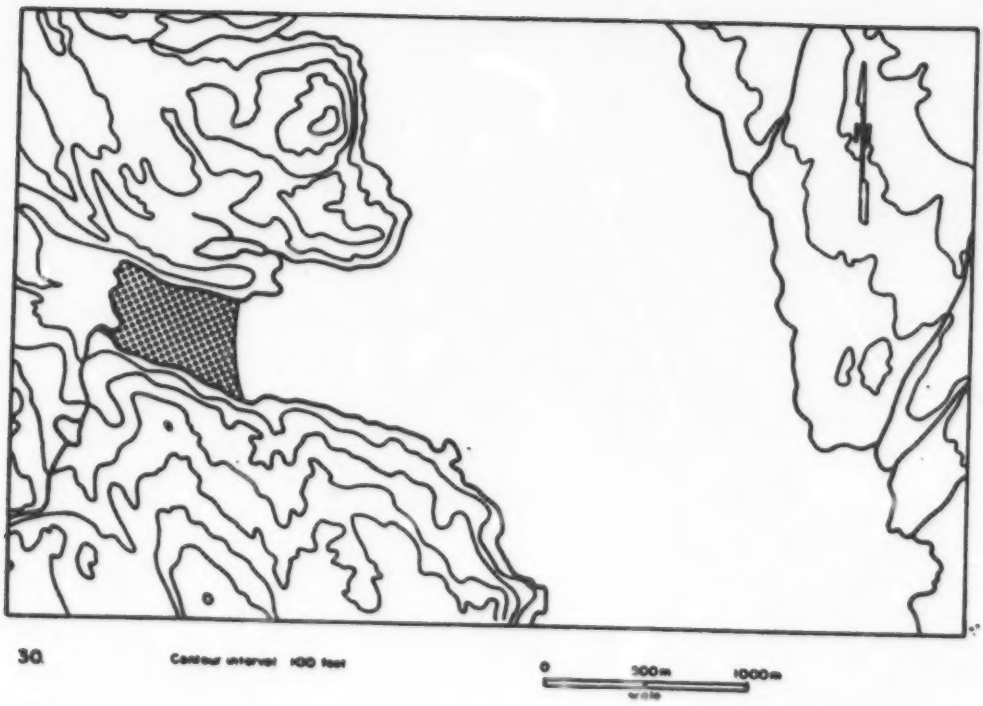


Figure A30 Ice conditions in Great Mosquito Cove, April 3, 1990.

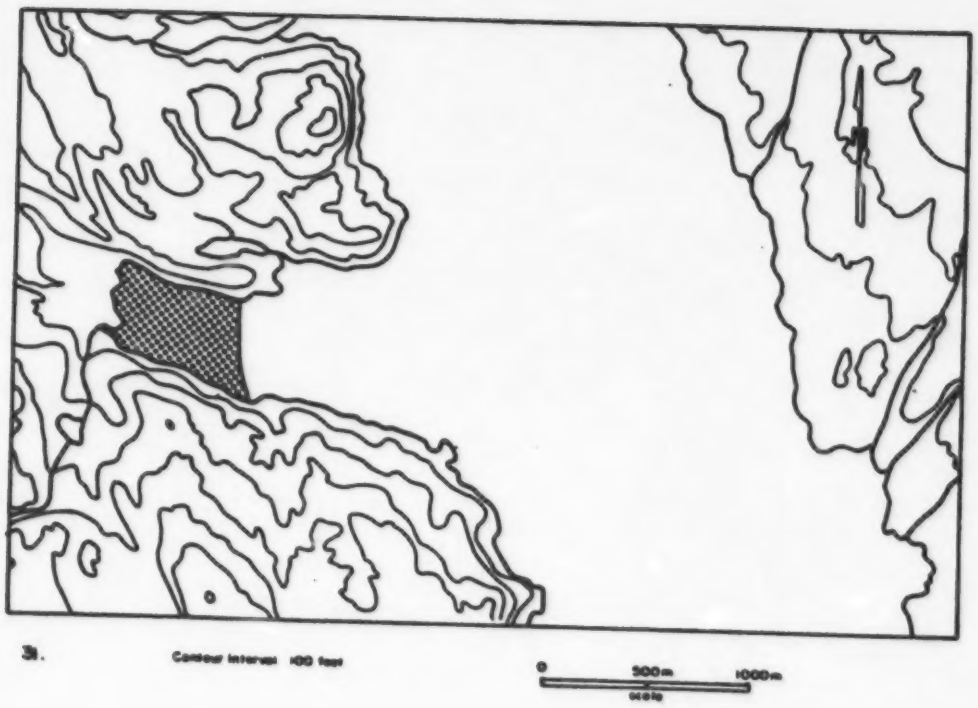


Figure A31 Ice conditions in Great Mosquito Cove, April 7, 1990.

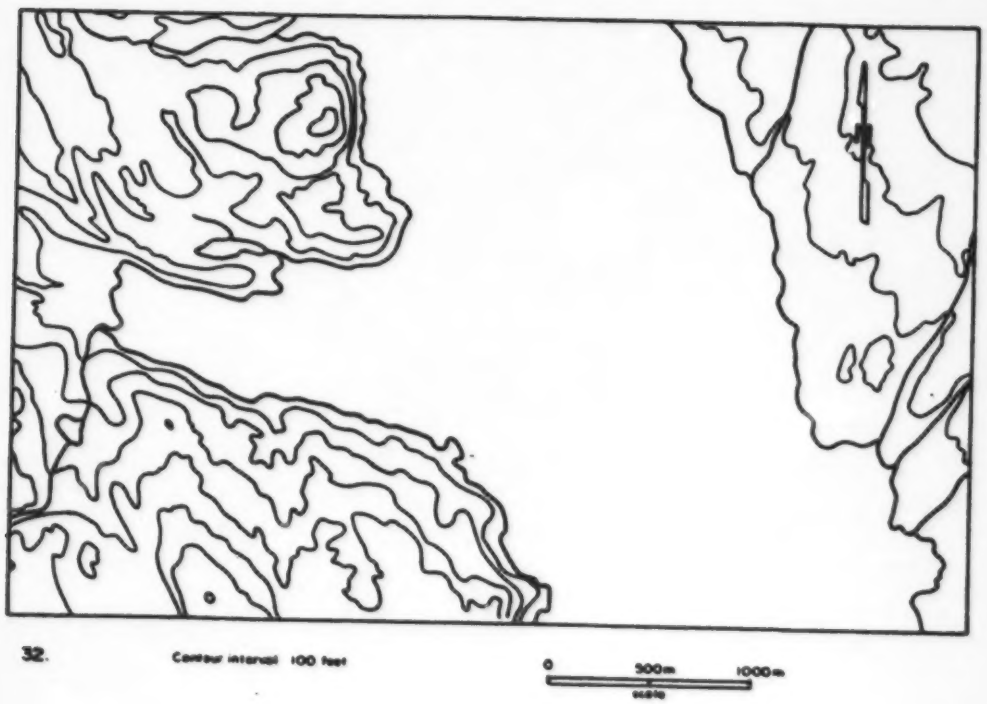


Figure A32 Ice conditions in Great Mosquito Cove, April 10, 1990.

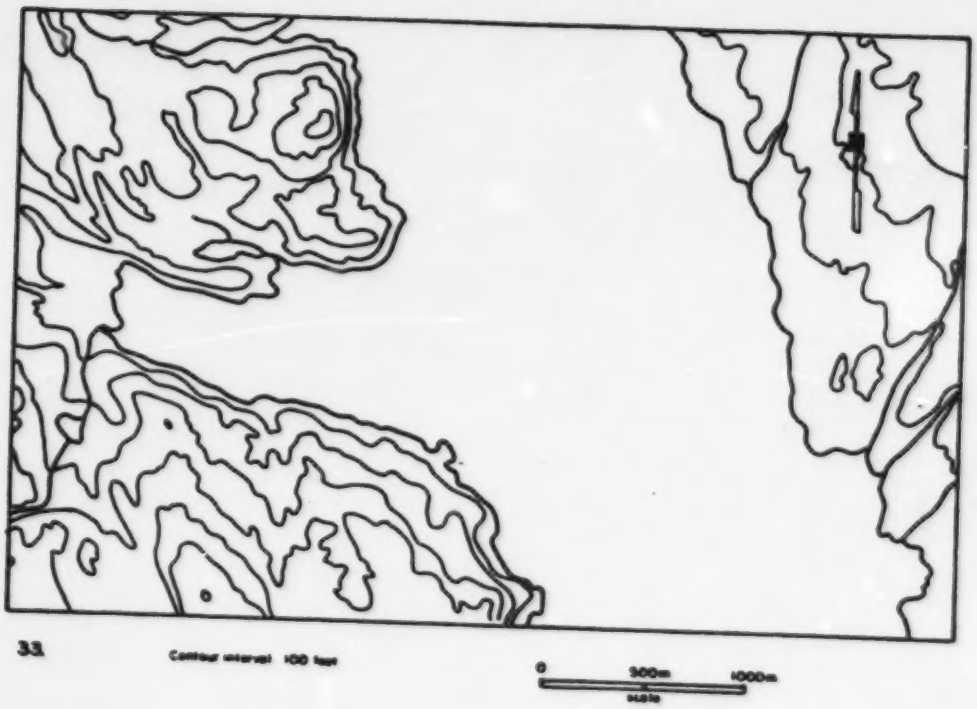


Figure A33 Ice conditions in Great Mosquito Cove, April 14, 1990.

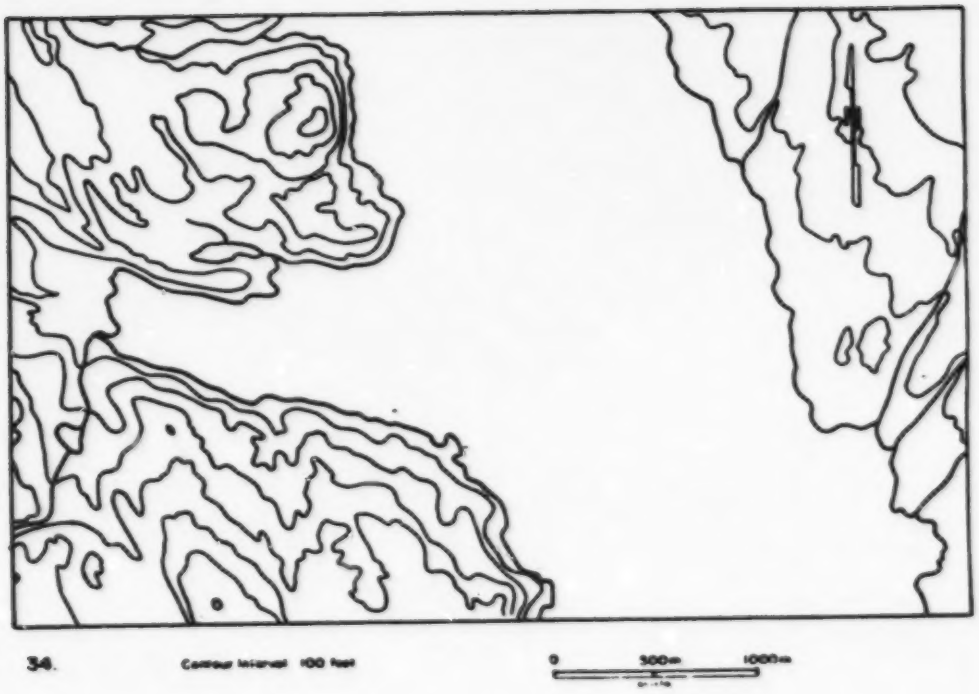


Figure A34 Ice conditions in Great Mosquito Cove, April 17, 1990.

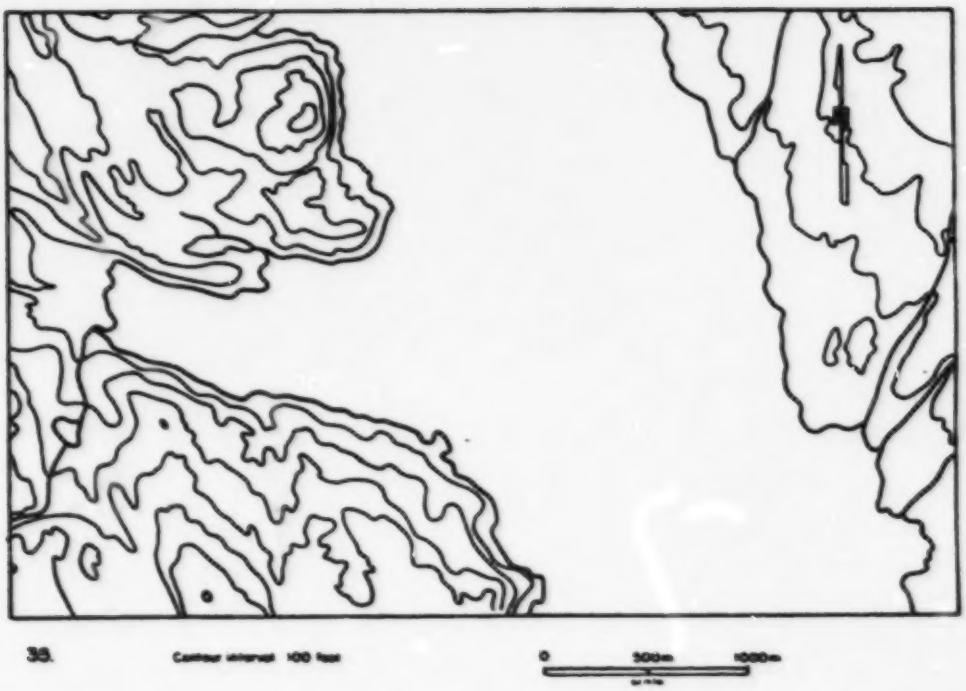


Figure A35 Ice conditions in Great Mosquito Cove, April 24, 1990.

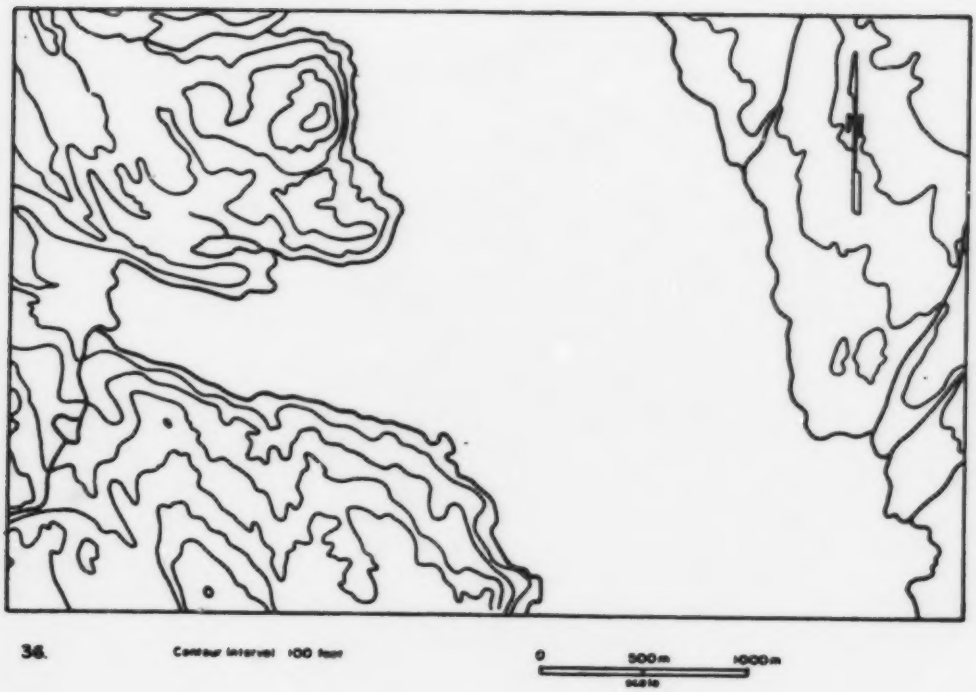


Figure A36 Ice conditions in Great Mosquito Cove, April 28, 1990.

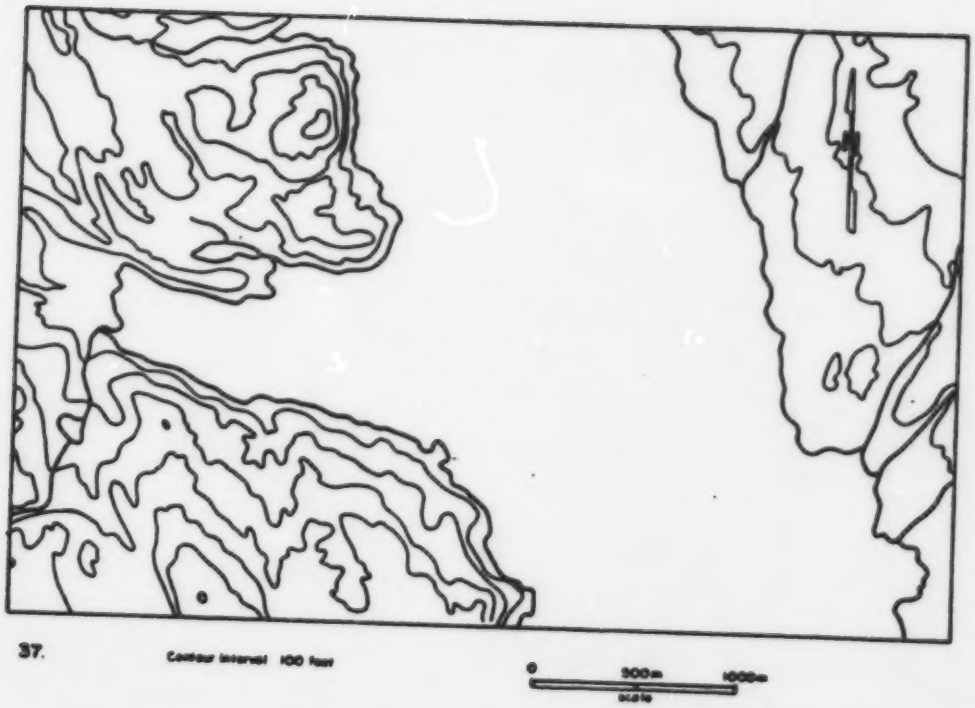


Figure A37 Ice conditions in Great Mosquito Cove, May 1, 1990.

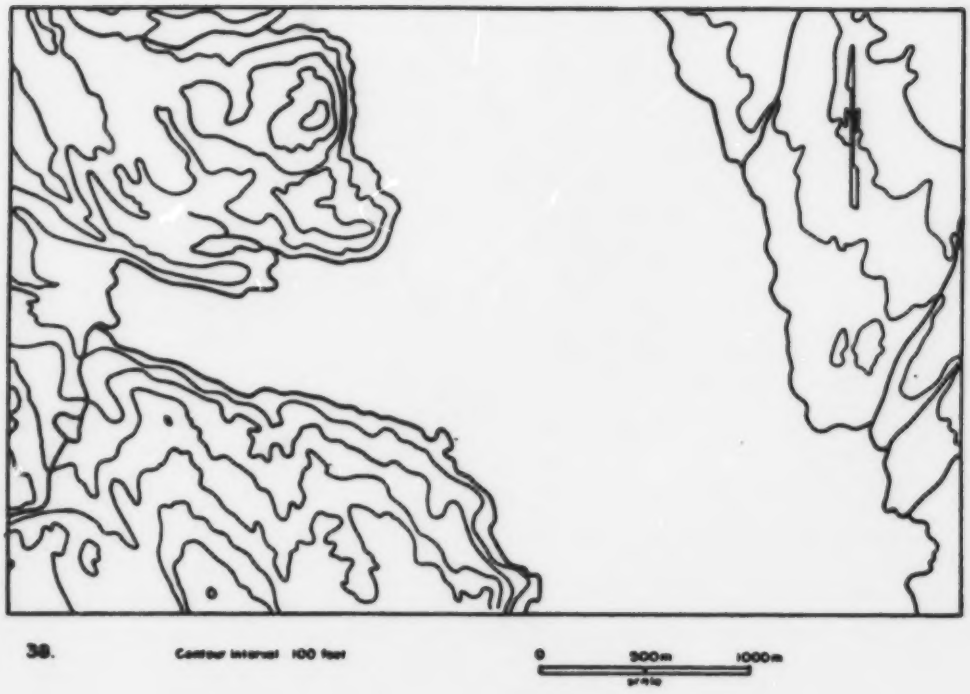


Figure A38 Ice conditions in Great Mosquito Cove, May 5, 1990.

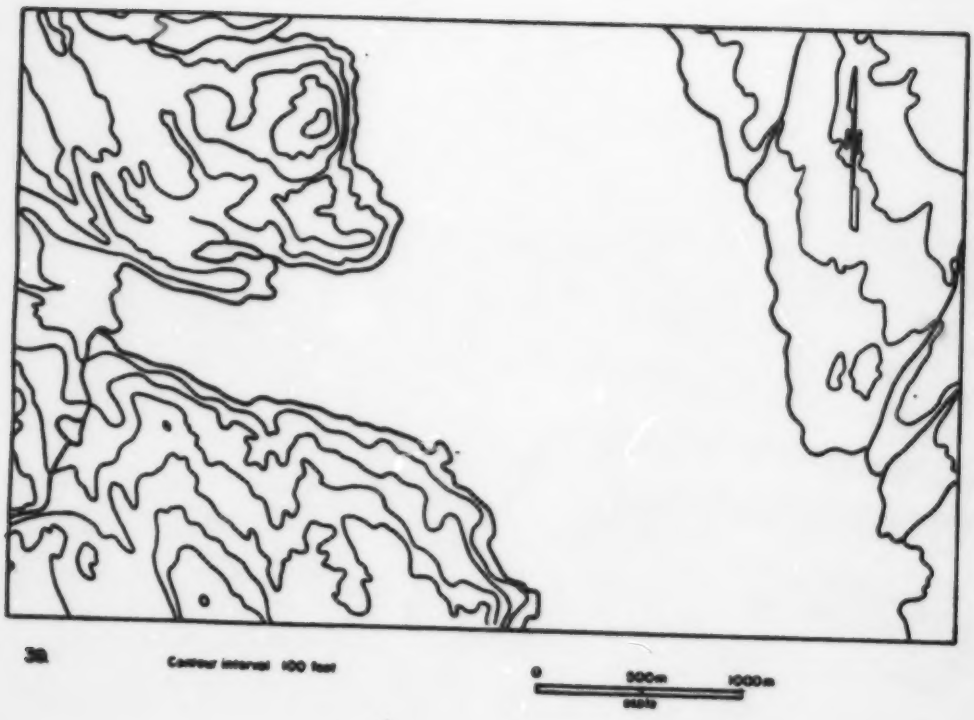


Figure A39 Ice conditions in Great Mosquito Cove, May 8, 1990.

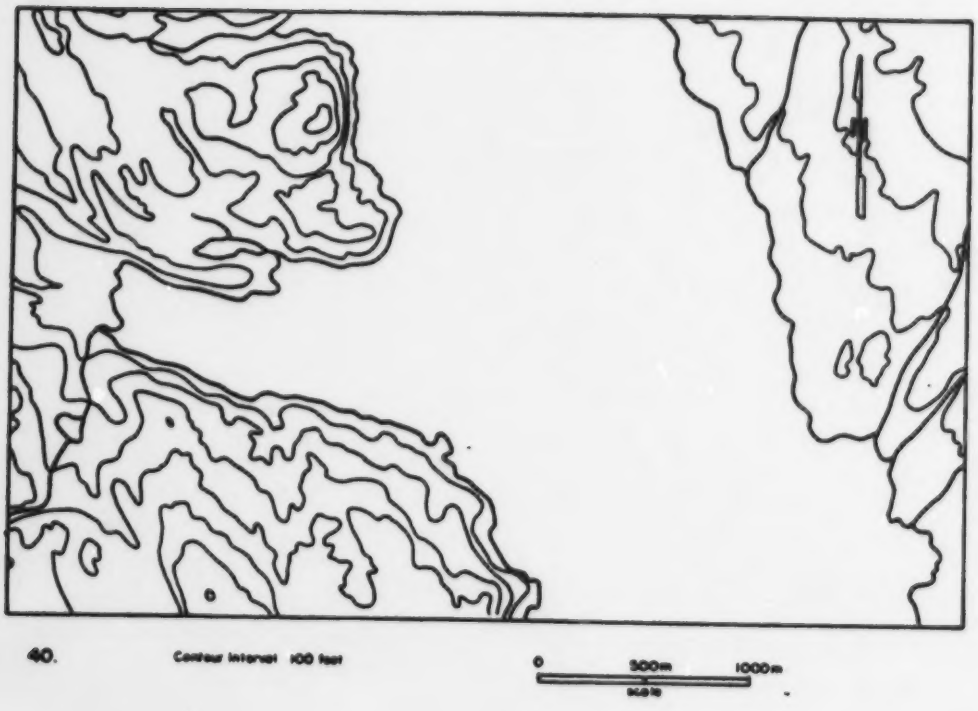


Figure A40 Ice conditions in Great Mosquito Cove, May 12, 1990.

Appendix B:

Selected Ice Terminology (after Weeks (1976))

Anchor Ice Submerged ice attached or anchored to the bottom.

Bergy Bit A piece of glacial ice 5 to 15 m in length, floating or grounded in water.

Breakup A general expression applied to the formation of a large number of fractures through an ice sheet, followed by rapid divergent motion of the separate fragments.

Fast Ice Sea ice of any origin that remains fast (attached with little horizontal motion) along a coast or to some other fixed object.

First Year Ice Sea ice of not more than one winter's growth.

Frazil Ice Fine spicules or plates of ice suspended in water.

Grease Ice A stage of freezing, later than frazil ice, in which the crystals have coagulated to form a soupy layer on the surface.

Grey Ice Young ice 10-15 cm thick.

Grey-White Ice Young ice 15-30 cm thick.

Growler A piece of glacial ice under 5 m in length, floating or grounded in water.

Iceberg A massive piece of ice with a freeboard of more than 5 m, which has broken away from a glacier.

Ice Sheet A general expression for a laterally continuous relatively undeformed piece of sea ice.

Large Iceberg An iceberg 120 to 220 m in length, 51 to 75 in height, and weighing about 10,000,000 tonnes.

Medium Iceberg An iceberg 60 to 120 m in length, 16 to 50 m in height, and about 2,000,000 tonnes.

New Ice A general term for recently formed ice, including frazil ice, grease ice, slush, and shuga.

Nilas A thin, elastic crust of ice up to 10 cm thick.

Pack Ice Any accumulation of sea ice other than fast ice.

Pancake Ice Predominately circular pieces of ice from 30 cm to 3 m in diameter, and up to 10 cm in thickness, with raised rims due to pieces striking against one another.

Pressure Ridge A general expression for any elongated ridge-like accumulation of broken ice.

Rafting A process whereby one piece of ice overrides another; most obvious in new and young ice.

Rotten Ice Sea ice which has become honeycombed and which is in an advanced stage of disintegration.

Shuga An accumulation of spongy white ice lumps a few centimetres across, formed from grease ice or slush, and sometimes anchor ice.

Slush Snow which is saturated and mixed with water on land or ice surfaces, or forms of a viscous mass floating in water after a snowfall.

Small Iceberg An iceberg 15 to 60 m in length, 5 to 15 m in height, and weighing about 100,000 tonnes.

Snow Ice The equi-granular ice that is produced when slush freezes completely.

Young Ice Ice in the transition stage between nilas and first year ice, 10 to 30 cm thick. May be subdivided into grey and grey-white ice.

Appendix C: Questionnaire

MOSQUITO COVE QUESTIONNAIRE

1. Show area of interest on topo map.

2. Past Ice:

   a) earliest appearance .....
   b) latest appearance .....

   c) earliest departure .....
   d) latest departure .....

   e) extreme max. thickness .....

   f) conditions in typical year .....
   .....
   .....
   .....
   .....
   .....

3. Pack Ice:

   a) earliest appearance .....
   b) latest appearance .....

   c) earliest departure .....
   d) latest departure .....

   e) extreme max. thickness .....

   f) conditions in typical year .....
   .....
   .....
   .....
   .....
   .....

4. Icebergs:

   a) frequency of occurrence .....
   .....
   .....

5. General Comments .....
   .....
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